ELECTROMAGNETIC COMPATIBILITY OF ELECTRIC POWER QUALITY MONITOR ACCORDING TO EN 61326 STANDARD

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ÖZGÜR YAMAN

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
ELECTRICAL AND ELECTRONICS ENGINEERING

DECEMBER 2007

Approval of the thesis:

ELECTROMAGNETIC COMPATIBILITY OF ELECTRIC POWER QUALITY MONITOR ACCORDING TO EN 61326 STANDARD

submitted by **ÖZGÜR YAMAN** in partial fulfillment of the requirements for the degree of **Master of Science in Electrical and Electronics Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen ____________
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. İsmet ERKMEN ____________
Head of Department, **Electrical and Electronics Engineering**

Prof. Dr. Muammer ERMİŞ ____________
Supervisor, **Electrical and Electronics Engineering Dept., METU**

Prof. Dr. Işık ÇADIRCI ____________
Co-Supervisor, **Electrical and Electronics Engineering Dept., Hacettepe University**

Examining Committee Members :

Prof. Dr. Gülbin DURAL ____________
Electrical and Electronics Engineering Dept., METU

Prof. Dr. Muammer ERMİŞ ____________
Electrical and Electronics Engineering Dept., METU

Prof. Dr. Işık ÇADIRCI ____________
Electrical and Electronics Engineering Dept., Hacettepe University

Prof. Dr. H.Bülent ERTAN ____________
Electrical and Electronics Engineering Dept., METU

Turan DEMİRCİ ____________
TÜBİTAK-UZAY

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name : Özgür Yaman

Signature :

ABSTRACT

ELECTROMAGNETIC COMPATIBILITY OF ELECTRIC POWER QUALITY MONITOR ACCORDING TO EN 61326 STANDARD

Yaman, Özgür
M.Sc., Department of Electrical and Electronics Engineering
Supervisor : Prof. Dr. Muammer ERMİŞ
Co-Supervisor: Prof. Dr. Işık ÇADIRCI

December 2007, 176 pages

In this thesis; Electromagnetic Compatibility (EMC) of Electric Power Quality Monitor developed within the scope of National Power Quality Project has been investigated according to EN 61326 standard. Both immunity and emission tests have been carried out in EMC laboratories of ELDAŞ and ASELSAN for the device under test. Necessary counter measures such as using electromagnetic interference (EMI) filters and transient voltage suppressors, shielding the case of device with EMI protective materials have been taken to satisfy the immunity and emission limits defined in the standard for the device, and their success have been verified by laboratory tests. This research work has been fully supported by Public Research Grant

Committee (KAMAG) of TÜBİTAK within the scope of National Power Quality Project (105G129).

Keywords: Electromagnetic Compatibility, Electric Power Quality Monitor, National Power Quality Project

ÖZ

ELEKTRİK GÜÇ KALİTESİ ÖLÇÜM CİHAZININ EN 61326 STANDARDINA GÖRE ELEKTROMANYETİK UYUMLULUĞU

Yaman, Özgür
Yüksek Lisans Tezi, Elektrik ve Elektronik Mühendisliği Bölümü
Tez Yöneticisi : Prof. Dr. Muammer ERMİŞ
Ortak Tez Yöneticisi : Prof. Dr. Işık ÇADIRCI

Aralık 2007, 176 sayfa

Bu tez çalışmasında; Güç Kalitesi Milli Projesi kapsamında geliştirilen Elektrik Güç Kalitesi Ölçüm Cihazının elektromanyetik uyumluluğu (EMU) EN 61326 standardına göre incelenmiştir. Deneyden geçirilen cihazın bağışıklık ve emisyon şartlarını kapsayan testler ELDAŞ ve ASELSAN EMC laboratuarlarında gerçekleştirilmiştir. Cihaz için tanımlanan bağışıklık ve emisyon seviyelerine göre elektromanyetik girişim filtreleri ve geçici gerilim değişimi önleyiciler kullanmak ve cihaz kutusunu elektromanyetik girişim önleyici maddelerle kaplamak gibi gerekli önlemler geliştirilmiş ve bu önlemler laboratuvar testleri ile sınanmıştır. Bu araştırma tamamen, Güç

Kalitesi Milli Projesi (105G129) kapsamında TÜBİTAK'ın Kamu Araştırmaları Grubu (KAMAG) tarafından desteklenmiştir.

Anahtar kelimeler: Elektromanyetik Uyumluluk, Elektrik Güç Kalitesi Ölçüm Cihazı, Güç Kalitesi Milli Projesi

To My Wife Derya

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisor Prof. Dr. Muammer ERMİŞ and my co-supervisor Prof. Dr. Işık ÇADIRCI for their guidance, advice, criticism, encouragements and insight throughout the research.

This research work has been fully supported by Public Research Grant Committee (KAMAG) of TÜBİTAK within the scope of National Power Quality Project (105G129).

I would like to thank to my colleagues EMC engineers Mr. Erdem AKPINAR and Mr.Yakup ERDOĞAN for sharing their knowledge and supporting me till the end of this research.

I would like to thank my whole family for their care on me from the beginning of my life and their trust on me that I could accomplish this task.

I would like to thank my company ASELSAN A.Ş. for their support on the every phase of this work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

PQ	:	Power Quality
EMI	:	Electromagnetic Interference
EMC	:	Electromagnetic Compatibility
CM	:	Common Mode
DM	:	Differential Mode
EUT	:	Equipment Under Test
EPQM	:	Electrical Power Quality Monitor
CE	:	Conducted Emission
RE	:	Radiated Emission
VCP	:	Vertical Coupling Plane
GTEM	:	Gigahertz Transverse Electromagnetic Cell
ESDS	:	Electrostatic Discharge Sensitive
HBM	:	Human Body Model

CHAPTER 1

INTRODUCTION

1.1 Need for Electromagnetic Compatibility (EMC)

Electromagnetic compatibility has always been an important topic in electrical engineering since electromagnetic fields generated by electrical circuits usually influence other equipment, and usually these circuits are influenced by the fields caused by other equipment. Generally, undisturbed continuous operation of the equipment has always been the main goal for design engineers, and of course, the equipment should not disturb the others while performing its normal operations.

In the environment, the quantity of the devices causing strong electromagnetic fields is increasing. For example, in today's world of communication, there has been a noticeable increase in the usage of wireless communication such as cellular phones, Bluetooth, Wi-Fi, etc. . As the basic working principle of wireless communication is the RF signal transmission and reception through air, all equipment are under risk of interferences from these sources. Of course, wireless communication is not the only culprit. As technology improves and more challenging needs arise, the designs are becoming more complicated. In electrical engineering, there is a tendency to decrease the signal voltage level, accordingly to decrease the size of the semiconductor devices used in an electrical circuit. This tendency causes the electrical circuits to be much more sensitive to electromagnetic fields. Therefore devices nearby could be the other culprits for interfering us. However, the designers should be aware that the opposite is also possible. The victim can be a culprit for others too. So the aim should be: Be immune to interferences. Do not cause any interference.

The electromagnetic compatibility gains importance day by day as the words such as “safety-related”, “high-reliability”, “mission-critical” come forward. EMC topic starts to take place in the first design stages of equipment. For example, EMI filtering, shielding or another precaution against EMI can, sometimes, be meaningless if your PCB layout is not good. Therefore EMI countermeasures should be evaluated at the beginning of the design. For this purpose, some electronic engineers have started to be more interested in EMC area, yielding the EMC engineering as an important part of electrical and electronics engineering. Nowadays, with the sophistication of EMC area, and discovery of new topics, the importance of EMC engineering increases.

1.2 EMC and Power Quality

In order to permanently enjoy today's commodity "electricity" on a high quality level, manufacturers need to ensure more than the electromagnetic compatibility of their equipment alone. This is where EMC meets power quality [1].

Institute of Electrical and Electronic Engineers (IEEE) Standard IEEE1100 defines power quality as “the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment.” A simpler and more concise definition might state: “Power quality (PQ) is a set of electrical boundaries that allows a piece of equipment to function in its intended manner without significant loss of performance or life expectancy.” [2].

Electromagnetic disturbances which are likely to disturb the correct operation of industrial equipment and processes are generally ranked in various classes related to conducted and radiated disturbance:

- low frequency (< 9 kHz),
- high frequency (≥ 9kHz),
- electrostatic discharge. [3]

Measurement of PQ usually involves characterising low frequency conducted electromagnetic disturbances (the range is widened to include transient overvoltages and transmission of signals on a power system):

- voltage dips and interruptions,
- harmonics and interharmonics,
- temporary power frequency overvoltages,
- swell,
- transient overvoltages,
- voltage fluctuations,
- voltage unbalance,
- power-frequency variations,
- DC in AC networks,
- signalling voltages. [3]

"Some machines even create their own power quality problems." is a magic sentence which is used in the book called "Power Quality" written by C.Sankaran [2]. This sentence shows the relation between the power quality and EMC clearly. Also it can be attributed as the EMC requirement of a power quality measurement instrument. Because these instruments are aimed to monitor the disturbances in a system and they do not have the privilege to disturb the system. They should also be immune to the interferences for accurate measurements.

In [4], a case study for achieving the EMC in equipment to meet both the emission and immunity test requirements by selecting proper EMI filters, using appropriate shielding aids, good grounding practices and transient protection devices is given.

Conducted emission test is defined for measuring the terminal disturbance of equipment. To pass this test, terminal disturbance levels of the equipment should stay below the required limits given in the standard. EMI filtering is a good solution for achieving this. Also EMI filtering affects radiated emission of the device because of the fact that conducted noise usually radiates from the cables of the equipment. In [5], the authors showed a design procedure for EMI filters for power electronics equipment. According to the study; a smaller, cheaper and optimized filter can be designed by separating the noise into the DM and CM components instead of dealing with the total noise, and filtering the dominant components. Design procedure is summarized in five steps: measuring the noise impedance, measuring the sink impedance, measuring the total conducted emission, setting up the total attenuation needed, and lastly choosing one filter topology and finding the corresponding filter components according to this topology.

A similar EMI filter design method for switching power supplies is given in [6]. In this study, CM and DM components are separated by measuring the CM and DM noise spectra by a simple test filter (e.g. a capcitor). The following steps are similar with the study given in [5].

In [7], a practical EMI filter design was implemented by separating conducted EMI noise into common mode and differential mode components by appropriate current probe measurements. Then CM and DM parts of the filter were designed by using the required attenuation levels for both type of noise, concerning the conducted emission levels given in respective standard.

EMI filtering helps both the conducted and radiated emissions, however other countermeasures should be taken too for radiated emissions. Shielding procedures are mentioned with their effects in the book written by

Oren Hartal [8]. The book states that suppression of electromagnetic fields by a conductive barrier or shield may be a simple, cost-effective method of solving the problem.

1.3 Scope of the Thesis

When the quality of electrical power supplied to equipment is deficient, performance degradation results [2]. So continuous monitoring of PQ is needed to detect the possible problems that can arise in a system. In this wise, EPQM (Electric Power Quality Monitor) is being designed by Tübitak-Uzay within the scope of National Power Quality Project. One of the goals of the National Power Quality Project is defined as to identify principles, approaches, hardware, and software requirements which will enable to monitor Power Quality parameters defined in IEC 61000-4-30 Std. “Electromagnetic compatibility (EMC); Testing and measurement techniques – Power quality measurement methods” continuously in the Turkish Electricity Transmission System and to carry out development activities accordingly.

As mentioned in the previous section, power quality measurement instruments do not have the privilege to disturb the system and to be disturbed by the system. So we have to ensure their electromagnetic compatibility for their proper operation according to a chosen EMC standard.

EMC standards ensure that conducted and radiated emissions are kept below defined levels. These standards also give conducted and radiated immunity levels which are usually higher than the related emission levels, guaranteeing that the equipment compatible to emission requirements will not disturb the equipment which satisfies the immunity requirements.

EMC usually affects the marketing in the countries, because when an electronic device is to enter the market; it is obvious that guaranteeing its electromagnetic compatibility instead of qualifying or restricting the operating areas is more meaningful.

If a research is done in the power quality market, it is observed that almost every power quality measurement instrument has EMC specifications. For example, Fluke 1750 Three-Phase Power Quality Recorder [9] product of Fluke Company fulfills EMC emission requirements of EN 61326 Std. - “Electrical equipment for measurement, control and laboratory use – EMC requirements” Class A. A product of the same company Fluke 345 Power Quality Clamp Meter [10] declares that it fulfills EMC emission requirements of EN 61326 Class A and immunity requirements of EN 61326 with “Performance Criterion B”. Dranetz BMI is another company dealing with PQ monitoring and it supplies PQ Analyzers that are provided to be electromagnetically compatible according to FCC – “Federal Communications Commission” regulations.

As seen from EMC requirements of PQ measurement instruments given above, two main EMC standards come forward: European EN standards which are developed by the European Committee for Electrotechnical Standardization (CENELEC) and FCC standards which are the general EMC requirements in the U.S. set by the Federal Communications Commission (FCC).

Concerning the possible future needs for EPQM such as putting a “CE Mark” on our product or being acceptable in the Common Market/European Economic Area, European EN standards have been chosen for this study.

European EN standards come forward in three types as basic, generic and product standards. So, next issue is to decide the type of the EMC standard that will be applied to the device.

As a product standard covers all EMC requirements for a certain product type, it also covers electrical safety requirements. Thus, a product standard takes preference over all other standards. Once it is determined that the device is within the scope of an applicable product family standard, then that standard should be followed. In this wise, it became more suitable to choose a product based standard for the EMC of EPQM. So EN 61326 standard has been chosen for EPQM. This standard is a product based standard which defines the EMC requirements for electrical equipment for measurement, control and laboratory use. Two main requirements, immunity and emission, are searched for EMC of the devices in this product standard.

In summary, EPQM is to be electromagnetic compatible according to EN 61326. Both immunity and emission tests have to be carried out for the device. Possibly there will be a need for counter measures in order to satisfy the immunity and emission limits defined in the standard for the device. Using electromagnetic interference (EMI) filters and transient voltage suppressors, shielding the case of device with EMI protective materials can be given as examples of these possible countermeasures. Finally, success of these countermeasures have to be verified by laboratory tests.

1.4 Organization of the Thesis

In this thesis, the electromagnetic compatibility of EPQM (Electric Power Quality Monitor) designed by Tübitak-Uzay within the scope of National Power Quality Project has been investigated using the regulations embodied in EN 61326 standard.

The study is generally accomplished in three phases. Phase 1: testing the EPQM according to the test procedures given in the respective standard. Phase 2: discussing the results and troubleshooting. Phase 3: repeating the testing of EPQM with the respective countermeasures. It should be noted that phase 1 is skipped in some immunity tests because of the risk that ESD, EFT/Burst and surge pulses can damage the device if necessary countermeasures are not taken before the conduction of the pulses.

Chapter 2 gives some theoretical background on EMC. The simulated situations in immunity standards such as ESD, EFT, power disturbances, etc. are explained by mentioning their sources. Some prevention techniques are given for such situations. Conducted and radiated electromagnetic emissions are mentioned by their causes and some filtering techniques and other possible countermeasures are given for these emissions.

The technical specifications for EPQM are given in chapter 3. Also, the questions like “which parts of EPQM are possible EMI sources” and “which parts are more possibly susceptible to interferences” have been assessed in this chapter.

Chapter 4 is about the emission tests defined in EN 61326. An approach for EMI filter design is given and according to this approach a filter is designed for attenuation of the conducted and radiated EMI of the EPQM. Results with and without filter are compared for each defined emission test.

Chapter 5 covers the immunity tests defined in EN 61326 standard. In this chapter, the countermeasures taken are explained, and results before and after these countermeasures are given for each defined immunity test.

Conclusions are given in Chapter 6. Results have been discussed and according to the performance criteria determined for each test, the parts of EPQM which should be of focal importance within the research have been pointed out.

CHAPTER 2

THEORETICAL BACKGROUND ON EMC

2.1 Electromagnetic Interference (EMI)

An incompatibility occurs when the operation of one equipment interferes with the operation of another. When the interaction is traced to the transfer of electromagnetic energy from the culprit equipment to the victim, it is termed electromagnetic interference. In order for this energy transfer to occur, a transfer mechanism or coupling path is necessary [11] (see Figure 2-1).

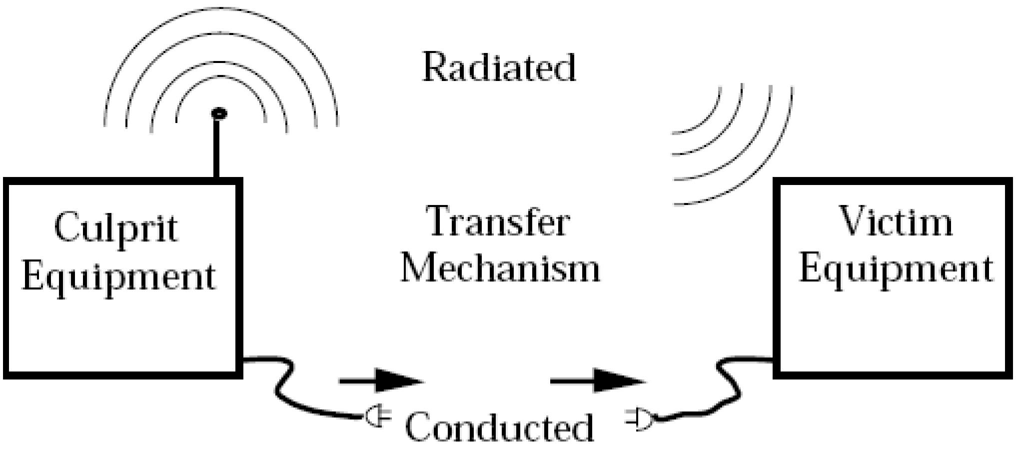


Figure 2-1: Transfer Mechanism

Electromagnetic Interference is defined as the influence of unwanted signals on devices and systems, making the operation of the device difficult or impossible. If a device is not EM-compatible, it is viewed as having an EMI problem [12].

An electromagnetic signal must have a “Source” or origin. The source then needs a “coupling path” to facilitate the transmission of the disturbance signal to the “Victim”. If one of these three elements is removed from the system, the disturbance problem is solved. The coupling path between source and victim does not have to be a conducting medium such as an electric conductor or dielectric. It can be coupled through the atmosphere as well. In most instances, the coupling path is a combination of conduction and radiation. One technique that can be used to minimize EMI-problems is to keep the disturbance signals from the source and across the coupling path below a certain level [12] (see Figure 2-2).

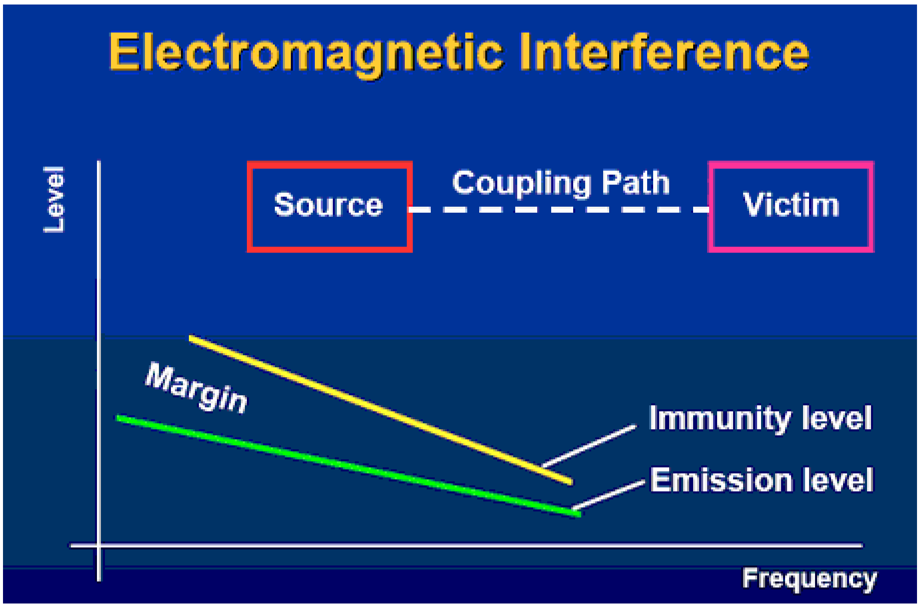


Figure 2-2: Electromagnetic Interference

2.2 Electromagnetic Compatibility

EMC stands for electromagnetic compatibility and is defined as the ability of equipment to function satisfactorily in its electromagnetic environment without introducing intolerable disturbances to anything in that environment. EMC requirements concern two basic concepts: emissions and immunity or susceptibility [13].

Electromagnetic compatibility is also used to describe the branch of electrical sciences which studies the related effects, such as Electromagnetic Interference. The goal of the EMC discipline is the correct operation, in a common electromagnetic environment, of different equipment which uses electromagnetic phenomena, and the avoidance of any interference effects [14].

In order to achieve this, EMC pursues two different kinds of issues. Emission issues are related to the unwanted generation of electromagnetic energy, and to the countermeasures which should be taken in order to reduce such generation and to avoid the escape of any remaining energies into the external environment. Susceptibility or immunity issues, in contrast, refer to the correct operation of electrical equipment in the presence of unplanned electromagnetic disturbances [14].

2.3 The Compatibility Gap

The increasing susceptibility of electronic equipment to electromagnetic influences is being paralleled by an increasing pollution of the electromagnetic environment. Susceptibility is a function partly of the adoption of VLSI technology in the form of microprocessors, both to achieve new tasks and for tasks that were previously tackled by electromechanical or analog means, and the accompanying reduction in the energy required of potentially disturbing factors. It is also a function of the increased penetration of radio communications, and the greater opportunities for interference to radio reception that result from the co-location of unintentional emitters and radio receivers [15].

At the same time more radio communications mean more transmitters and an increase in the average RF field strengths to which equipment are exposed. Also, the proliferation of digital electronics means an increase in low-level emissions which affect radio reception, a phenomenon which has been aptly described as a form of electromagnetic “smog” [15].

These concepts can be graphically presented in the form of a narrowing electromagnetic compatibility gap, as in Figure 2-3 [15].

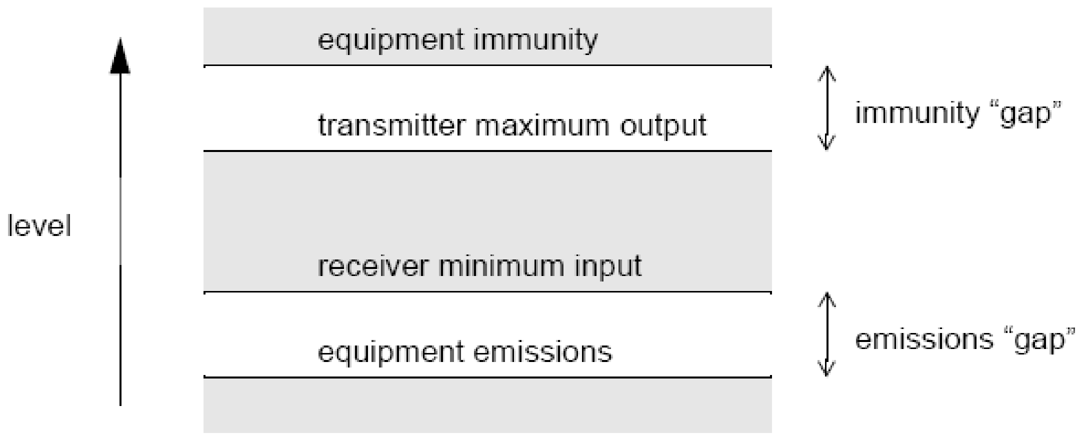


Figure 2-3: The EMC Gap

2.4 Fundamental Definitons

Radio Frequency (RF): A frequency range containing coherent electromagnetic radiation of energy useful for communication purposes – roughly the range from 10 kHz to 100 GHz. This energy may be transmitted as a byproduct of an electronic device’s operation. RF is transmitted through two basic modes:

- **Radiated Emissions:** The component of RF energy that is transmitted through a medium as an electromagnetic field. Although RF energy is usually transmitted through free space, other modes of field transmission may occur.
- **Conducted Emissions:** The component of RF energy that is transmitted through a medium as a propagating wave, generally through a wire or interconnecting cables [16].

Susceptibility: A relative measure of a device or system's propensity to be disrupted or damaged by EMI exposure to an incident field of signal. It is the lack of immunity [16].

Immunity: A relative measure of a device or system's ability to withstand EMI exposure while maintaining a predefined performance level.

- **Electrostatic Discharge (ESD):** A transfer of electric charge between bodies of different electrostatic potential in proximity or through direct contact. This definition is observed as a high-voltage pulse that may cause damage or loss of functionality to susceptible devices.
- **Radiated Immunity:** A product's relative ability to withstand electromagnetic energy that arrives via free-space propagation.
- **Conducted Immunity:** A product's relative ability to withstand electromagnetic energy that penetrates it through external cables, power cords, and I/O interconnects [16].

Containment: A process whereby RF energy is prevented from exiting an enclosure, generally by shielding a product within a metal enclosure (Faraday cage or Gaussian structure) or by using a plastic housing with RF conductive paint. Reciprocally, we can also speak of containment as preventing RF energy from entering the enclosure [16].

Suppression: The process of reducing or eliminating RF energy that exists without relying on a secondary method, such as a metal housing or chassis. Suppression may include shielding and filtering as well [16].

2.4.1 Decibel(dB) Expressions

Conducted current level using current measuring probe given probe factor in dB(ohm) and probe terminal voltage in dBμV [17] (See Eqn. 2.1).

$$dB\mu A = dB\mu V - dB(ohm) \qquad \text{(Eqn. 2.1)}$$

Conducted current level, given probe factor in Zt (ohms) and terminal voltage in dBμV [17] (See Eqn. 2.2).

$$dB\mu A = dB\mu V - 20\log(Zt) \qquad \text{(Eqn. 2.2)}$$

2.4.2 Standard Units

Mathematical expressions for dBμV and dBμA are given in Eqn. 2.3 and Eqn. 2.4.

$$dB\mu V: \qquad dB\mu V = 20log\left[\frac{signal\ strength\ (\mu V)}{1\ \mu V}\right] \qquad \text{(Eqn. 2.3)} \qquad [11]$$

$$dB\mu A: \qquad dB\mu A = 20log\left[\frac{signal\ strength\ (\mu A)}{1\ \mu A}\right] \qquad \text{(Eqn. 2.4)} \qquad [11]$$

If a voltage to current relationship (i.e., V = I x R) is being evaluated in logarithmic form, then R is a constant of proportionality between voltage and current and takes on the same “20 • log” character [11] (See Eqn. 2.5):

$$dB\Omega: \qquad dB\Omega = 20log\left[\frac{resistance\ (\Omega)}{1\,\Omega}\right] \qquad \text{(Eqn. 2.5)}$$

2.5 Types of EMI

EMI is usually classified into two types depending on how it is propagated:

- Conducted EMI is the noise fed back from a system onto the AC or DC power line or signal lines. This noise is generally in the frequency range of 10KHz to 30MHz. It usually has a common mode component and a differential mode component. The common mode component appears as a voltage on both line and neutral leads with respect to ground or earth while the differential mode appears between the line and neutral leads. To suppress conducted EMI, LC networks are usually used [18].
- Radiated EMI comes in the form of electromagnetic waves radiating directly from the circuitry and leads of a system. A common example is the AC power cord of the system which can act as a transmitting antenna for radiated EMI. Generally ranging from 30MHz to 1GHz, this type of noise can be effectively suppressed by metal shielding around the source [18].

EMI is quantified and controlled by four categories. These categories encompass all the possible permutations of radiated and conducted mechanisms combined with control of emissions from the equipment and with control of susceptibility of the equipment. The four categories are the followings:

(a) Conducted emissions (CE)

(b) Conducted susceptibility (CS)

(c) Radiated emissions (RE)

(d) Radiated susceptibility (RS). [11]

2.5.1 Conducted EMI

There are two major sources of noise, common mode and differential mode. Common mode noise (see Figure 2-4) comes from common mode current. Common mode energy is common to both lines in a single phase system. This energy travels on all the lines, or wires, in the same direction, and this energy is between all these wires and ground. Because the same level is on both wires at the same time, no attenuation is given by any device between the lines [19].

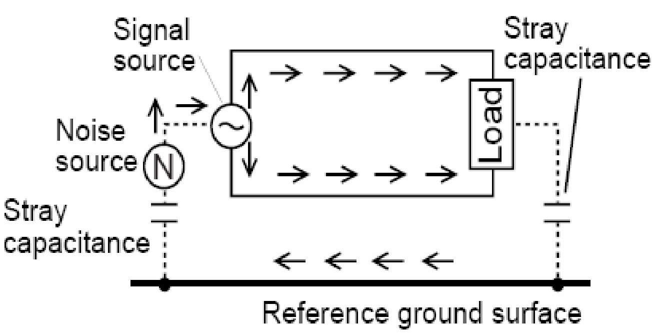


Figure 2-4: Common Mode Noise

Common mode noise from common mode current always exists on cables entering the device. The common mode current can be easily measured by using a high frequency clamp on current probe and a spectrum analyzer. A current probe with a response range of up to 250 MHz should be sufficient [19].

Differential mode noise (see Figure 2-5) is the opposite of common mode noise. This noise is produced by current flowing along either the live or neutral conductor and returning by the other. This produces a noise voltage between the live and neutral conductors [19].

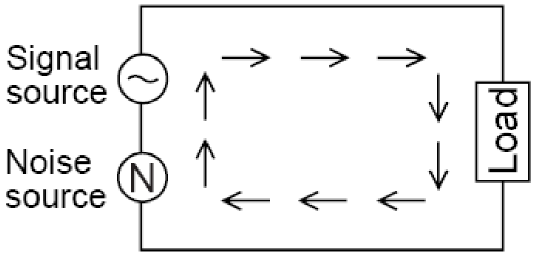


Figure 2-5: Differential Mode Noise

2.5.1.1 Differential Mode Component

Differential mode EMI appears as a voltage between the supply lines of the equipment. The resulting current circulates through the supply lines and the source. None flows through the earth conductor [18].

For pure differential mode signals (See Figure 2-6):

$$V_1 = - V_2 \qquad [20]$$

Magnitudes are equal, phase difference is 180º.

$$V_{DIFF} = V_1 - V_2 \qquad [20]$$

No AC current flows to ground because of symmetry of V1 and V2 with respect to ground. All differential mode current (I_D) flows through the LOAD [20] (see Figure 2-6).

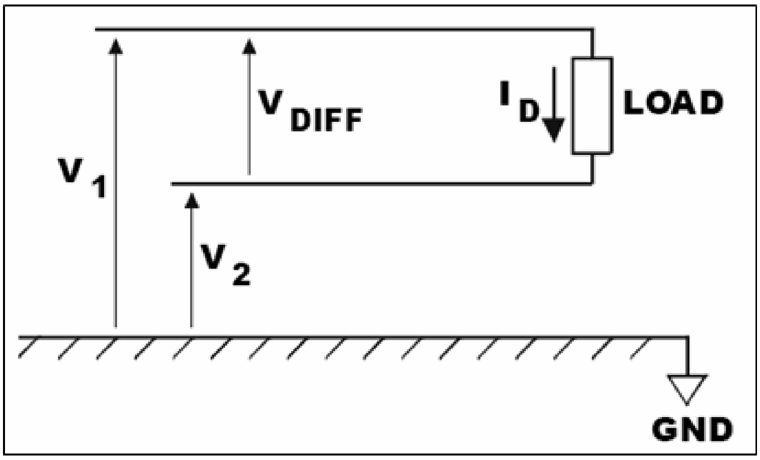


Figure 2-6: Differential Mode Current

The instantaneous AC sum of the two voltages (V1 + V2) is always zero. Note that only the AC component of this common-mode voltage can radiate and may potentially cause EMI problems. The common-mode voltage may be at some DC level, but this DC component does not generate radio-frequency noise [20] (see Figure 2-7).

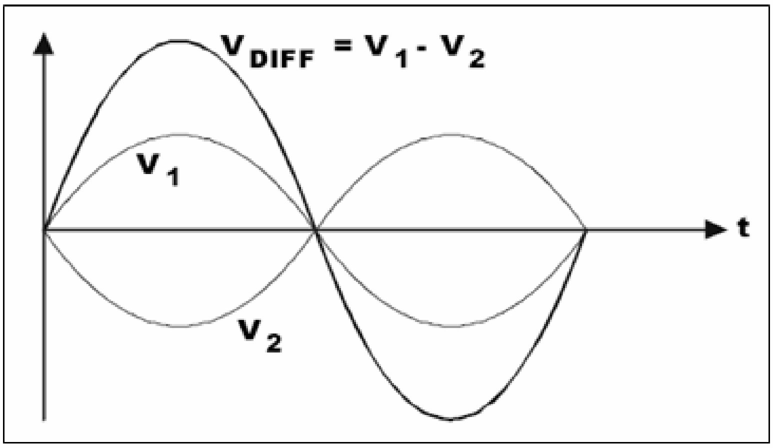


Figure 2-7: Differential Mode Voltage

For pure differential-mode signals, the currents in each of the wires in a pair travel in opposite directions (see Figure 2-8). If the pair is uniformly wound, these opposing currents produce equal and oppositely polarized electro-magnetic fields that cancel each other out [20].

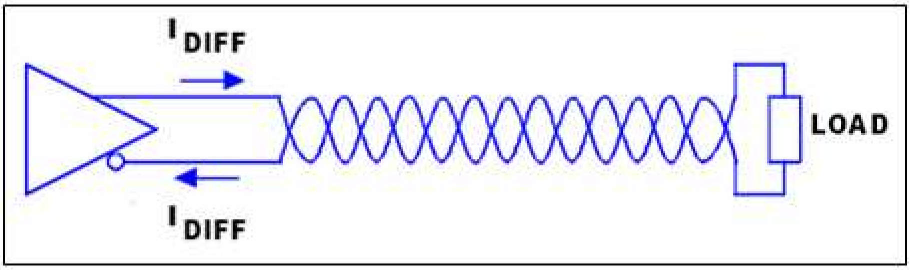


Figure 2-8: Differential Current in a pair

Even with the signal source sending perfectly balanced differential signal, if the two signal paths are not the same, the generated electro-magnetic fields will not be exactly equal and opposite and so will not exactly cancel. This asymmetry may also contribute significantly to RFI radiation. This process is called "differential to common-mode conversion" [20].

2.5.1.2 Common Mode Component

Common mode EMI appears as a voltage on both lines with respect to earth. Common mode current flows through both supply lines to earth. If the system has no protective earth connection, common mode current will flow through the capacitance between the case of the system and earth [18].

For pure common mode signals (See Figure 2-9):

$$V_1 = V_2 = V_{COM} \qquad [20]$$

Magnitudes are equal, phase difference is 0 º.

$$V_3 = 0 \qquad [20]$$

No current flows in the load because there is no potential difference across it. All common mode current (I_C) flows to GND via parasitic capacitance between the cable and GND [20] (see Figure 2-9).

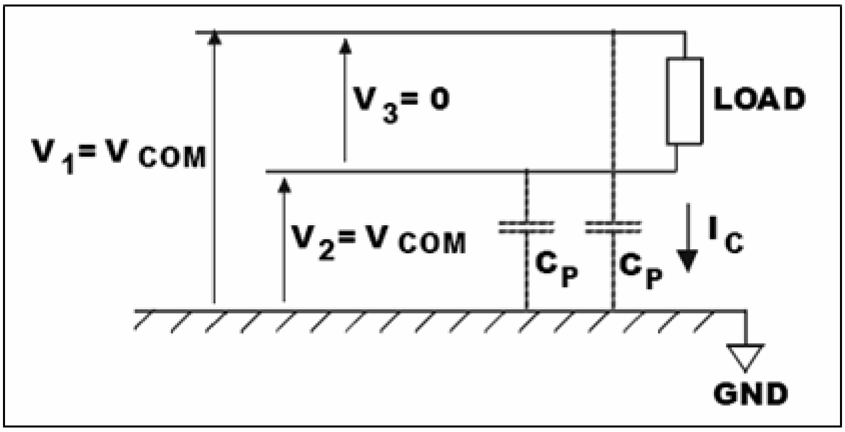


Figure 2-9: Common Mode Current

The instantaneous <u>sum</u> of the two voltages V1 and V2 is non-zero. The potential of the cable pair varies with respect to ground. This varying potential gives rise to electromagnetic radiation from the cable [20] (see Figure 2-10).

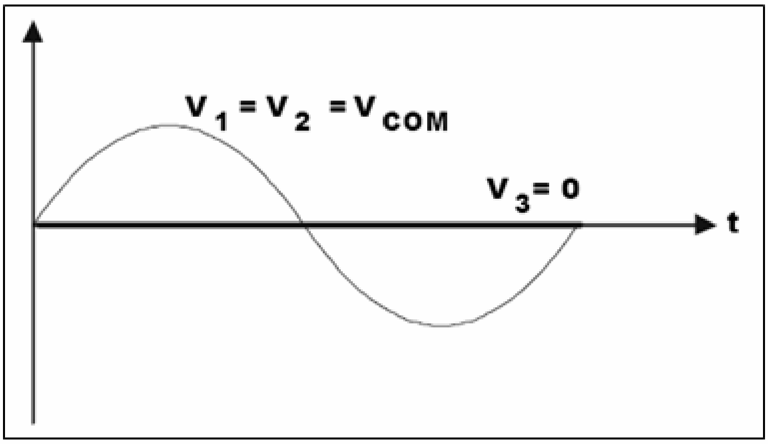


Figure 2-10: Common Mode Voltage

Common-mode current I_{com} flows both in both wires in the same direction, and returns to GND via parasitic capacitance C_p (see Figure 2-11). In this case, the currents generate magnetic fields with equal magnitude and polarity, which do not cancel each other out. The common mode current is able to generate an electromagnetic field outside the spiral wound pair, which acts just like an antenna [20].

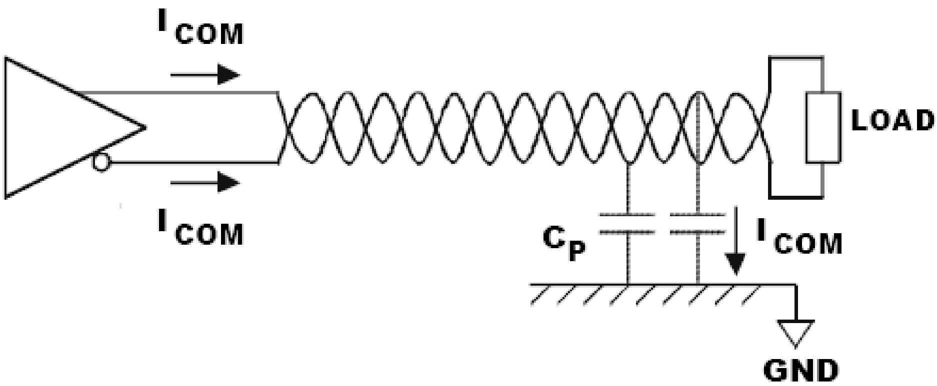


Figure 2-11: Common Mode Current in a pair wire

2.5.1.3 Mixed Signals

In real life, signals on balanced cable pairs contain both differential- and common mode components. However, the effects of each component can still be analyzed independently [20].

As will be seen below, only common-mode signals will emit radio-frequency (RF) noise, causing systems to potentially fail EMI tests, for which most modern countries have regulations [20] (see Figure 2-12, Figure 2-13).

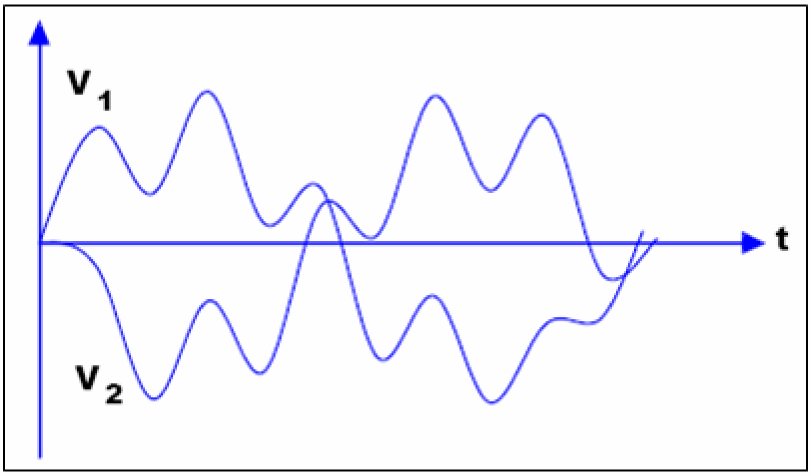


Figure 2-12: Mixed Signal

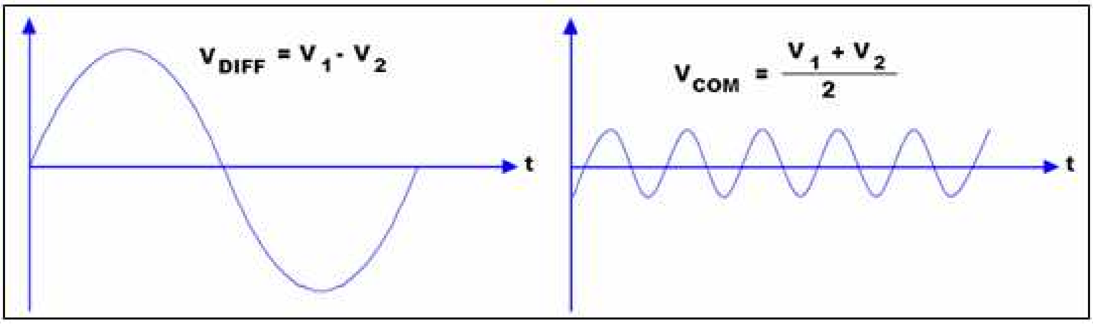


Figure 2-13: Separated Common and Differential Mode Signals

2.5.2 Radiated EMI

Radiated RF energy consists of both magnetic and electric fields. With each field there are two primary modes of signal transfer: common mode and differential mode. It is impossible to determine the type of current flow when the field is measured by an antenna. The common mode is generally the more prominent mode of interference propagation [21].

One field will be dominant, either electric or magnetic. Both fields exist simultaneously; however, one field will have a larger amplitude or field strength than the other except at some physical distance from the source of the energy. This distance is where both fields create a propagating plane wave that has the wave impedance value of approximately 377 Ω (impedance of free space) [21].

Undesired radiated RF energy is generally observed within the frequency range of approximately 100 kHz–300 GHz, which is the frequency range most often used for communication purposes [21].

2.5.2.1 Radiation from the PCB

In most equipment, the primary sources are currents flowing in circuits (clocks, video and data drivers, and other oscillators) that are mounted on printed circuit boards. Some of the energy is radiated directly from the pcb, which can be modelled as a small loop antenna carrying the interference current (See Figure 2-14). Most pcb loops count as “small” at emission frequencies of up to a few hundred MHz. When the dimensions approach λ/4 the currents at different points on the loop appear out of phase at a distance, so that the effect is to reduce the field strength at any given point [15].

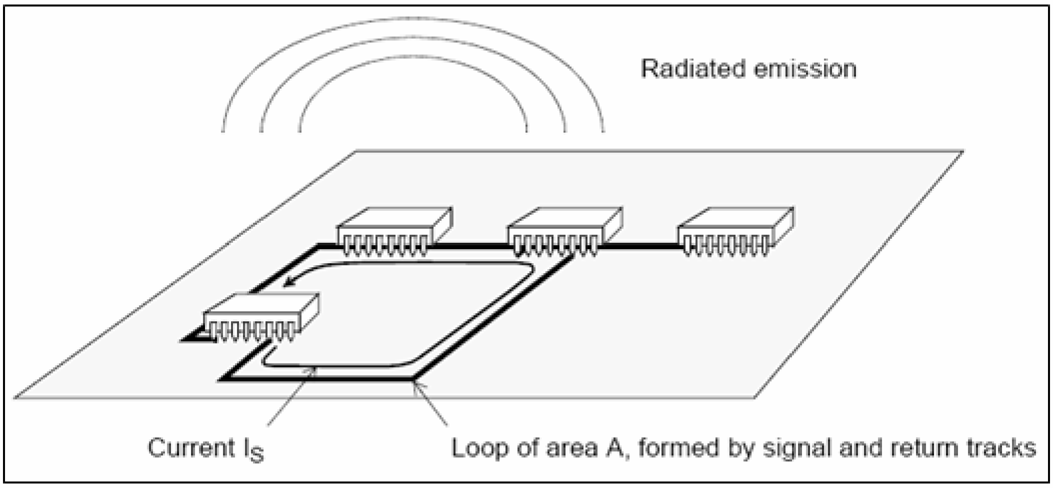


Figure 2-14: PCB Radiation Emissions

2.5.2.2 Radiation from Cables

Fortunately (from some viewpoints) radiated coupling at VHF tends to be dominated by cable emissions, rather than by direct radiation from the pcb. This is for the simple reason that typical cables resonate in the 30-100MHz region and their radiating efficiency is higher than pcb structures at these frequencies. The interference current is generated in common mode from ground noise developed across the PCB or elsewhere in the equipment and may flow along the conductors, or along the shield of a shielded cable [15].

The model for cable radiation at lower frequencies (See Figure 2-15) is a short ($L < \lambda/4$) monopole antenna over a ground plane [15].

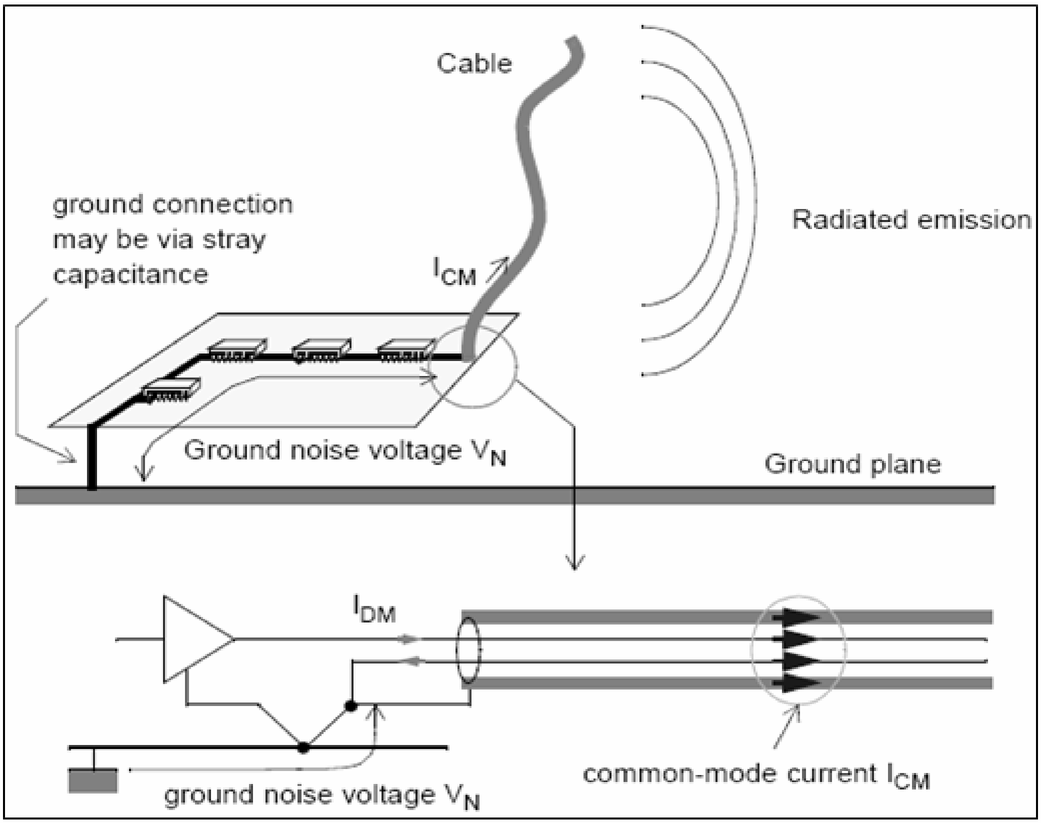


Figure 2-15: Cable Radiation Emissions

2.6 Electrostatic Discharge (ESD) and EMC

2.6.1 Background

The age of electronics brought with it new problems associated with static electricity and electrostatic discharge, and, as electronic devices became faster and smaller, their sensitivity to ESD increased. Today, ESD impacts productivity and product reliability in virtually every aspect of today's electronics environment [22].

Despite a great deal of effort during the past decade, ESD still affects production yields, manufacturing costs, product quality, product reliability, and profitability. The cost of damaged devices themselves ranges from only a few cents for a simple diode to several hundred dollars for complex hybrids. When associated costs of repair and rework, shipping, labor, and overhead are included, clearly the opportunities exist for significant improvements [22].

2.6.2 Generation of Electrostatic Discharge

Static electricity is defined as an electrical charge caused by an imbalance of electrons on the surface of a material. This imbalance of electrons produces an electric field that can be measured and that can influence other objects at a distance. *Electrostatic discharge* is defined as the transfer of charge between bodies at different electrical potentials [22].

Electrostatic discharge can change the electrical characteristics of a semiconductor device, degrading or destroying it. Electrostatic discharge also may upset the normal operation of an electronic system, causing equipment malfunction or failure[22].

2.6.3 What Causes Electronic Devices to Fail?

ESD damage is usually caused by one of three events: direct electrostatic discharge to the device, electrostatic discharge from the device or field-induced discharges. Damage to an electrostatic discharge sensitive (ESDS) device by the ESD event is determined by the device's ability to dissipate the energy of the discharge or withstand the voltage levels involved. This is known as the device's ESD sensitivity [22].

2.6.3.1 Discharge to the Device

An ESD event can occur when any charged conductor (including the human body) discharges to an ESDS device. The most common cause of electrostatic damage is the direct transfer of electrostatic charge from the human body or a charged material to the ESDS device [22].

2.6.3.2 Discharge from the Device

The transfer of charge from an ESDS device is also an ESD event. Static charge may accumulate on the ESDS device itself through handling or contact with packaging materials, worksurfaces, or machine surfaces. This frequently occurs when a device moves across a surface or vibrates in a package. The model used to simulate the transfer of charge from an ESDS device is referred to as the Charged Device Model (CDM). The capacitance and energies involved are different from those of a discharge to the ESDS device. In some cases, a CDM event can be more destructive than the human body model (HBM) for some devices [22].

2.6.3.3 Field Induced Discharges

Another event that can directly or indirectly damage devices is termed Field Induction. As noted earlier, whenever any object becomes electrostatically charged, there is an electrostatic field associated with that charge. If an ESDS device is placed in that electrostatic field, a charge may be induced on the device. If the device is then momentarily grounded while within the electrostatic field, a transfer of charge from the device occurs as a CDM event. If the device is removed from the region of the electrostatic field and grounded again, a second CDM event will occur as charge (of opposite polarity from the first event) is transferred from the device [22].

2.6.4 ESD Levels

An ESD event is characterized by a very slow buildup of energy (often in the tens of seconds), followed by a very rapid breakdown (typically in the nanoseconds or even picoseconds). This fast breakdown causes many EMI problems in modern electronic equipment. With typical pulse rise times in the nanosecond range, you see equivalent EMI frequencies in the hundreds of megahertz. Due to this high speed/high frequency, ESD energy can damage circuits, bounce grounds, and even cause upsets through electromagnetic coupling [23].

2.6.4.1 Human Body Model

Figure 2-16 shows some typical ESD waveforms levels based on recent human-body models, and Figure 2-17 shows the equivalent circuit of a human [23].

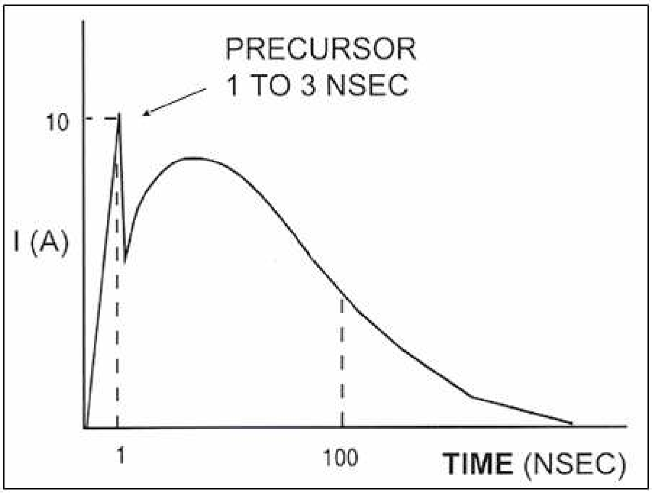


Figure 2-16: Typical ESD waveform for human-body model

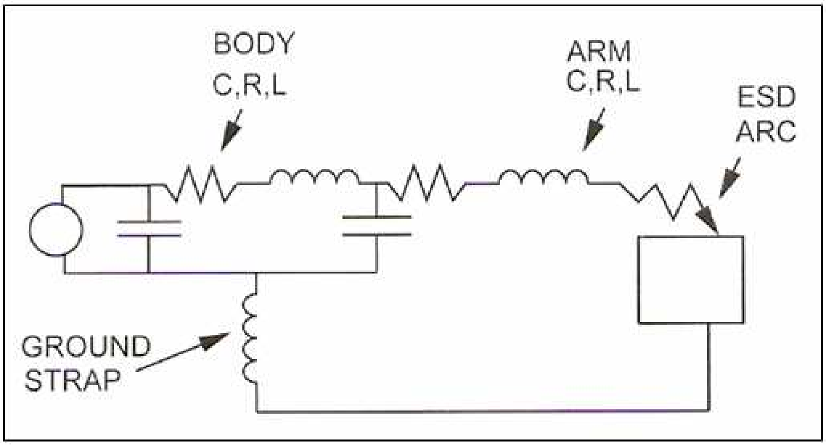


Figure 2-17: Equivalent ESD Circuit of Human

Peak currents can exceed tens of amps, and rise times are in the nanosecond range. The initial spike, or precursor, assumes the human body has distributed capacitance (most in the body, some in the arm) rather than simple lumped capacitance [23].

More recent research indicates that additional, faster, small precursors also exist, due to distributed capacitance in the fingers [23].

In addition to current, the rise time is also important. ESD is a fast transient, so two parameters are important: peak level and rate of change (di/dt). In the EMI world, you often convert rise times to an equivalent EMI frequency, where $F=1/(\pi t_r)$ where t_r = rise time. It's based on the Fourier transform as shown in Figure 2-18. With a typical 1-nsec rise time, the equivalent ESD frequency is more than 300 MHz. This is no longer static electricity, and it requires VHF (not dc) design techniques [23].

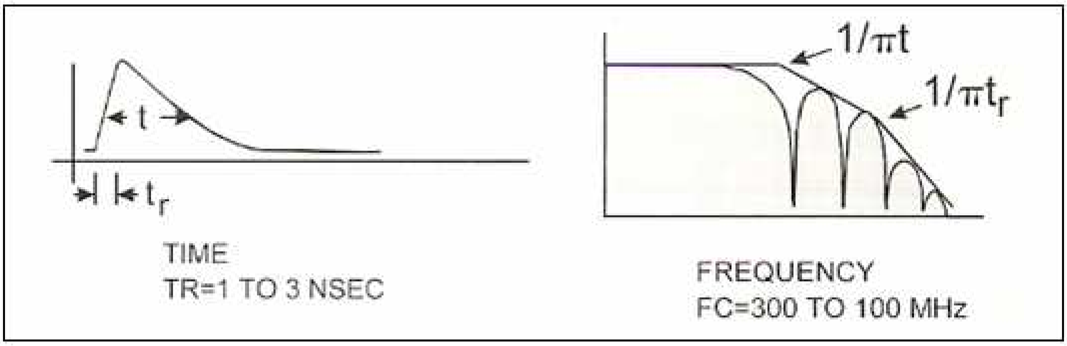


Figure 2-18: Time versus Frequency For ESD

2.6.4.2 Effects of Humidity and Resistance

Humidity helps because the moisture reduces the surface impedances, allowing charges to recombine at a faster rate. The same effect occurs when using static dissipative materials, which also provide a lower surface impedance on materials such as countertops or packing material [23].

As a result, it's more difficult to develop the high voltage necessary for an ESD breakdown. In fact, studies have shown that at greater than 50% humidity, it's difficult for humans to exceed about 2000V. At 5% humidity, that level can reach 15,000V or more [23].

Table 2.1 shows typical electrostatic voltages produced in both high and low humidity environments [24].

Table 2.1: Electrostatic voltages and humidity

	Electrostatic Potential (V)	
Means of static generation	10 – 20 % Relative humidity	65 – 90 % Relative humidity
• Walking across a carpet	35,000	1,500
• Walking on a vinyl floor	12,000	250
• Picking up a polythene bag	20,000	1,200
• Getting up from a polyurethane foam chair	18,000	1,500

So humidity does not really control ESD, it just prevents high-voltage levels from occuring in the first place. Even with high humidity, though, you can still have problems [23].

2.6.5 ESD Failure Modes

Figure 2-19 shows four ESD failure modes [23].

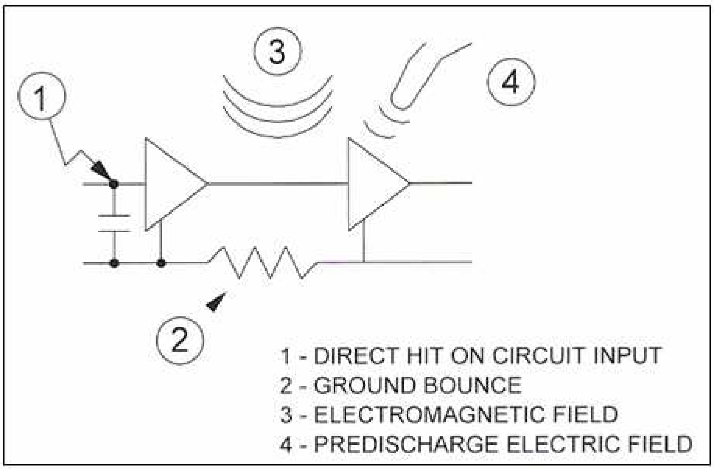


Figure 2-19: Four ESD Failures

The first failure mode is upset or damage due to ESD current flowing directly through a vulnerable circuit. Any current injected into a pin is likely to damage a device. That's why direct connections to any IC from the outside world, such as a connector or keyboard, are not a good idea [23].

The second failure mode is upset or damage due to ESD current *flowing in the circuit ground.* The usual result is an upset, but the ground bounce can drive CMOS circuits into latch-up. During latch-up, ESD does not actually do the damage; it just sets things up for the power supply to destroy the part [23].

The third failure mode is upset due to electromagnetic-field coupling. This effect rarely results in damage, because typically only a small fraction of the ESD energy is coupled into the vulnerable circuit. This mode is highly dependent on the rise time (dI/dt), circuit-loop areas, and presence of shielding. This effect is often referred to as the indirect-coupling mode [23].

The fourth failure mode is due to the predischarge electric field. It's uncommon, although it occurs with very sensitive analog circuits with very high input impedances [23].

2.6.6 ESD Failure Types

2.6.6.1 Catastrophic Failure

When an electronic device is exposed to an ESD event, it may no longer function. The ESD event may have caused a metal melt, junction breakdown, or oxide failure. The device's circuitry is permanently damaged causing the device fail. Such failures usually can be detected when the device is tested before shipment. If the ESD event occurs after test, the damage will go undetected until the device fails in operation [22].

2.6.6.2 Latent Defect

A latent defect, on the other hand, is more difficult to identify. A device that is exposed to an ESD event may be partially degraded, yet continue to perform its intended function. However, the operating life of the device may be reduced dramatically. A product or system incorporating devices with latent defects may experience premature failure after the user places them in service. Such failures are usually costly to repair and in some applications may create personnel hazards [22].

2.6.7 ESD-Prevention Techniques

You can often prevent ESD with adequate insulation. If ESD occurs, you can divert the ESD currents away from vulnerable circuit inputs through filters or transient suppressors. Alternately, you can limit ESD currents with small resistors or ferrites whenever possible. Better to dissipate ESD energy in a resistor or ferrite than in an IC [23].

A second ESD strategy is to determine the most vulnerable internal circuits-the ones most likely to be upset by ground bounce or electromagnetic effects, such as resets, interrupts, and critical controllines [23].

The game plan is to limit the amount of electromagnetic-field coupling or ground bounce. You can protect these critical circuits individually with filters or coIlectively with cable or cabinet shielding [23].

2.6.7.1 Circuit-level Protection

Good ESD protection begins at the circuit level. You should use transient protection or filters on all external lines, plus filters on the critical internal lines. In no case should there be a direct connection from an IC to an exposed external point, because it would be like hooking a lightning rod to your system. Figure 2-20 shows a summary of circuit recommendations [23].

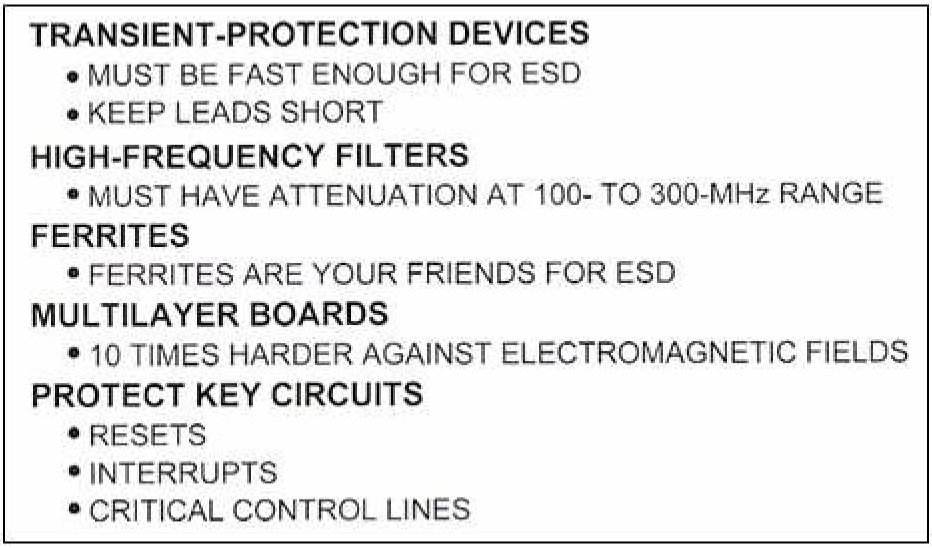


Figure 2-20: ESD Circuit Recommendations

Transient protection devices must be fast enough to act on the ESD [23].

The best devices are silicon based, such as zeners or Tranzorbs. Tranzorb devices are preferable because they have a larger die area and are designed to act quickly and dissipate a lot of energy for their size [23].

If you have the choice, you should ground your transient protectors or filters to the case, not to the circuit ground [23].

2.6.7.2 Protecting Connectors and Cables

Cables and connectors are critical in ESD control. Cables can act as both unintended antennas and unintended conductors for ESD energy and must be addressed any time ESD is a threat. Furthermore, even the best cable can be rendered ineffective with poor connectors, so you must consider the cable and connectors together as a system. Figure 2-21 contains some design guidelines hardening the cables and connectors against ESD [23].

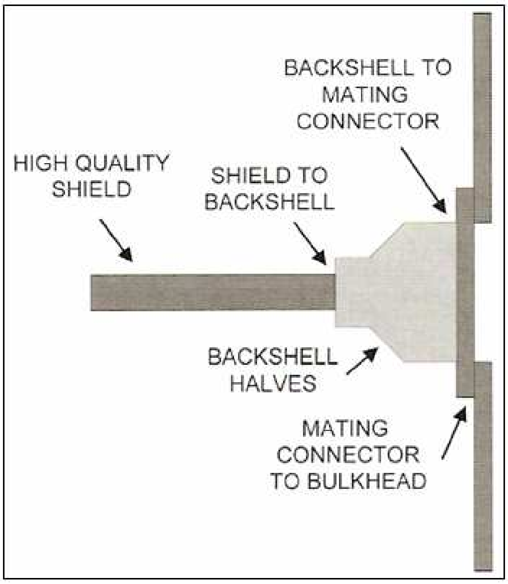


Figure 2-21: ESD Proofing Cables&Connectors

The objective is to provide full 360^0 coverage all the way from the cabIe shield to the chassis. If you can not shield the external cables, then you must provide filtering or transient protection on every conductor, including signal grounds [23].

2.6.7.3 Shielding

Thin shielding material works well. Because ESD fields are high-frequency fields, thin conductive materials provide high levels of shielding. For example, aluminium foil provides more than 100 dB of attenuation at 300 MHz, which is more than adequate for most ESD problems. Thin metal coatings (such as nickel paints) provide at least 40 dB in this range, and other materials (such as vacuum plating or electroless deposition) are usually good for 80 dB or more [23].

Slots and seams can destroy ESD shielding. The real problem with ESD shielding is leakage due to discontinuities, such as slots and seams. A rule of thumb in the EMI world is to limit the longest dimension of any opening to $^{1}/_{20}$ of a wavelength at the highest frequency of concern. For an ESD frequency of 300 MHz, slots or seams must be less than 5 cm, or about 2 in. Even 2 in. May be too long because an opening this size provides only 20 dB of attenuation through the slot. For 40 dB of attenuation, you need to reduce openings to 5 mm, about $^{1}/_{5}$ in. [23].

2.6.7.4 Software

Obviously, software will not work on ESD damage, nor will it work on systems without a computer or microprocessor. But with even a few lines of code, you can change an ESD disaster into an ESD success. These same software techniques work equally well on other EMI sources [23].

ESD can flip any bit in memory, resulting in program flow or data errors. ESD can also corrupt data on I/O and busses. As a minimum, you should have "returns" in unused interrupt locations, parity in memory, and type and range checking on I/O data. Simple checksums in critical data tables and self-monitoring programs also help [23].

2.7 Power Disturbances as EMI Problems

With more and more electronic equipment being plugged into the power mains network, potential interference occurs. These problems include power-line disturbances, electrical fast transients (EFT), power sag and surges, voltage variations (high/low voltage levels), lightning transients, and power line harmonics. Older products and power supplies were generally not affected by these disturbances. With newer, high frequency switching power supplies, these disturbances are starting to become noticeable as the switching components consume AC voltage generally on the crest of the waveform, not the complete waveform [16].

Analog and digital devices respond differently to power-line disturbances. Digital circuits are affected by spikes on the power system (EFT and lightning), as well as failure due to excessively high or low voltage levels. Analog devices generally operate on voltage levels, which may be degraded by a disturbance changing the reference level of the system's power source [16].

2.7.1 Types of Power Disturbances

Disturbances divide into five areas: voltage variations, frequency variations, waveform distortions, transients, and continuous electrical noise [23] (See Figure 2-22).

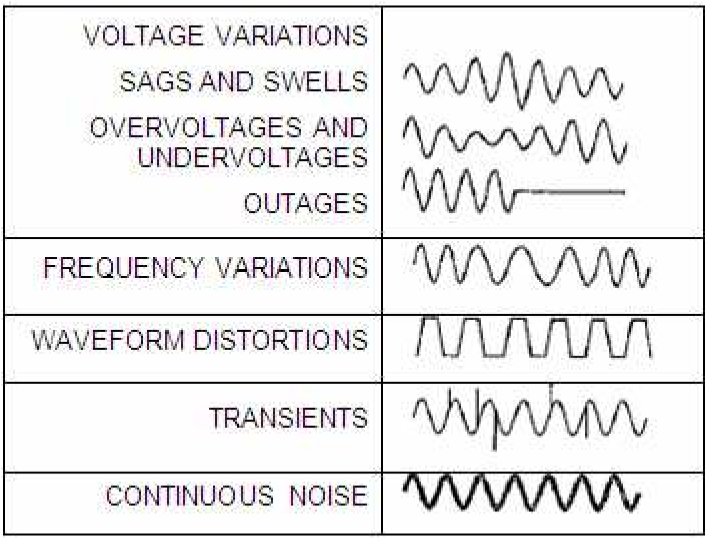


Figure 2-22: Types of Power Disturbances

Voltage variations. Convention divides them into three areas, based on duration. Voltage increases or decreases lasting from one-half cycle to a few seconds are called *swells and sags*. Voltage increases or decreases lasting longer than a few seconds are called *overvoltages and undervoltages*. Long-term losses of power (more than a few seconds) are called *interruptions or outages*. Voltage variations of less than one-half cycle are classed as *transients* [23].

Power utilities and users can cause sags and undervoltages. Some examples of utility-caused sags and undervoltages are voltage drops, which result from clearing faults, and brownouts which deliberate reductions of voltage during times of peak demand [23].

Swells and overvoltages, on the other hand, are almost exclusively utility-caused and result from sudden load changes or corrections of power factor [23].

Interruptions or outages can last from a few seconds to several hours or more and are usually caused by severe weather, transformer failures, accidents, or tripping of circuit breakers [23].

Frequency variations are changes in the sinusoidal frequency, usually due to poor generator regulation. Frequency variations can be a concern for small, independent power systems, particularly as the load changes. [23].

Waveform distortions include distortions of both current and voltage from a pure sine wave. Because any waveform other than a sine wave contains harmonics, waveform distortion is often referred to as harmonic distortion [23].

Transients are short-term disturbances (much less than a cycle, or 16.6 msec at 60 Hz, 20 msec at 50 Hz), which either increase (spike) or decrease (notch) the voltage waveform. Transients can last from nano-seconds to a few milliseconds, and amplitudes range from a few volts to thousands of volts [23].

Typical utility- transient sources include lightning, power-factor capacitor switching, and power-distribution faults. Typical facility- transient sources include motors (and other inductive loads) and mechanical switch and relay contacts [23].

2.7.2 Power-Disturbance Failure Modes

Failures can range from major damage to minor upset. Furthermore, different types of disturbances affect different parts of the system [23] (See Figure 2-23).

DIGITAL UPSET

- DUE TO SPIKES OR EFT

ANALOG UPSET

- DUE TO SAGS/SWELLS OR UNDERVOLTAGES/ OVERVOLTAGES

MEMORY LOSS

- DUE TO ENERGY STARVATION FROM UNDER-VOLTAGES OR OUTAGES

DAMAGE

- DUE TO HIGH-VOLTAGE TRANSIENTS,SUCH AS LIGHTNING

Figure 2-23: Power-Disturbance Failure Modes

The most likely causes of damage are high-voltage transients. The most severe is the lightning transient (as much as 6000V/2000A), which is often used as a worstcase test for all transients. If your equipment can pass this test, it probably will not be damaged by any other power-transient test [23].

The most likely causes of upset in digital electronics are high slew rates. In this case, it’s not the high levels, but the high dV/dt or dI/dt that causes problems [23].

Thanks to their low bandwidths, analog circuits are usually immune to fast transients on power lines. The circuits can be vulnerable, however, to slow variations such as sags and swells. These effects are critical in low-level stages in which small amounts of power modulation may be amplified by subsequent stages. This situation is really no different from amplitude modulation of a radio transmitter [23].

2.7.3 Protection Devices

Transient protectors, which divert the energy above preset voltage levels, include three type of devices: gas tubes, metal-oxide varistors (MOVs), and silicon zener devices. Each type has pros and cons, depending on operating speeds and energy capabilities [23].

You can divide transient protectors into two categories: clamps and crowbars. The clamp simply limits the voltage at a given threshold, and the crowbar provides a momentary short circuit when the voltage threshold is exceeded [23].

Zener diodes and MOVs are clamp protectors. They operate by limiting the voltage to a fixed level and diverting the rest of the energy. Because the clamp devices must dissipate the energy internally, they are typically rated in joules of energy. Their response time is fast, and zeners are faster than MOVs. The MOV devices, however, are generally available with a much higher joule rating, making them more robust in power-line protection [23].

EMI filters, unlike transient protectors, are linear devices that provide energy storage. Thus, they attenuate both spikes and notches in the power waveform. Because they are linear, however, they act proportionally, rather than clamp voltages to a fixed level. Filters are best suited for removing low levels of continuous RF energy, although they do attenuate high-speed (high-frequency) transients as well [23].

2.8 Transient Suppression

2.8.1 Background

Transient surge voltages are a major cause of poor reliability. Surge voltages can also cause erratic behavior in control circuits and effect the normal operation of electronics. Transient surge voltages can usually be attributed to:

- Sudden load changes in adjacent circuits
- Power source fluctuations
- Coupled electronic disturbances via cables
- Opening or closing of switch contacts
- Lightning
- ESD [25]

The power supply and data cables are common entry points for conducted and coupled transient surge voltages. In many systems, a common power supply is shared by a number of electronic modules. The modules are also connected to each other through communication buses that are often located in the same wire bundle as the power lines. The parasitic cable capacitances and inductances provide a path for the power line surge voltages to be coupled into the data lines [25].

All transient suppressors and surge suppressors operate on the voltage divider principle (See Figure 2-24):

- A blocking device detects excessive current flow, and increases its resistance sharply to hold the load current below some limit.
- A shunting device detects excessive voltage, and switches to a low impedance state so that the excess current goes through it, and not through the load. [26]

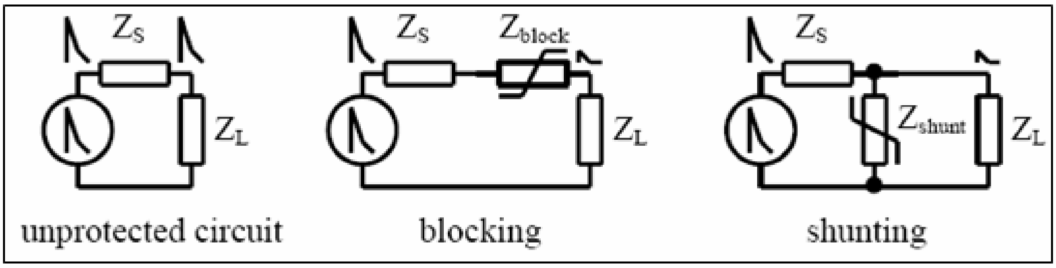


Figure 2-24: Voltage Division with Transient/Surge Protectors

Shunting devices are a lot easier to design and build, because insulators and semiconductors breakdown under high voltage—suddenly conducting lots of current. The challenge is:

- Maintaining low leakage current until we reach the threshold voltage.
- Controlling the threshold voltage.
- Maintaining low impedance after we reach the threshold voltage.
- Returning to a low-leakage state when the transient or surge is over.
- Not destroying or degrading the device in the process. [26]

2.8.2 The Effect of Transients

When transients occur on power lines, they affect the output voltage of the power source in the equipment and find their way into the electronic circuitry. If the transient is above the danger level of the supply, it will destroy it. If not, it may cause data errors, flase indications,etc. Sometimes these mulfunctions disappear when the transients fades, and at other times, permanent failure is the result. Transients also tend to radiate high-frequency broadband fields which cause EMI via the cables through which they flow. A typical example is radio frequency interference caused by ignition systems and electrical motors using brush commutators [8].

2.8.3 What is TVS?

Transient Voltage Suppressors (TVS's) are devices used to protect vulnerable circuits from electrical overstress such as that caused by electrostatic discharge, inductive load switching and induced lightning. Within the TVS, damaging voltage spikes are limited by clamping or avalanche action of a rugged silicon pn junction which reduces the amplitude of the transient to a nondestructive level [27].

In a circuit, the TVS should be "invisible" until a transient appears. Electrical parameters such as breakdown voltage (V(BR)), standby (leakage) current (ID), and capacitance should have no effect on normal circuit performance [27].

Transients of several thousand Volts can be 'clamped' to a safe level by the TVS [27] (See Figure 2-25).

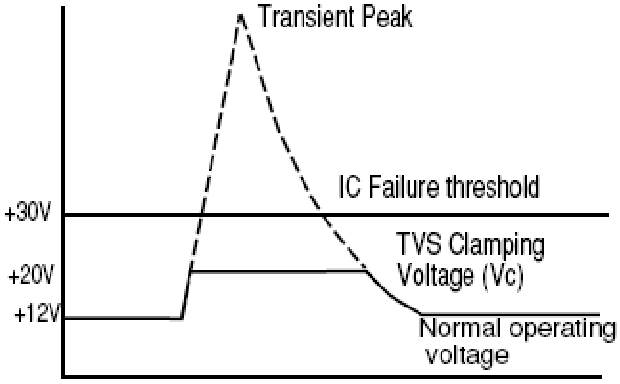


Figure 2-25: Clamping to a Safe Level

Transient current is diverted to ground through TVS; the voltage seen by the protected load is limited to the clamping voltage level of the TVS [27] (See Figure 2-26).

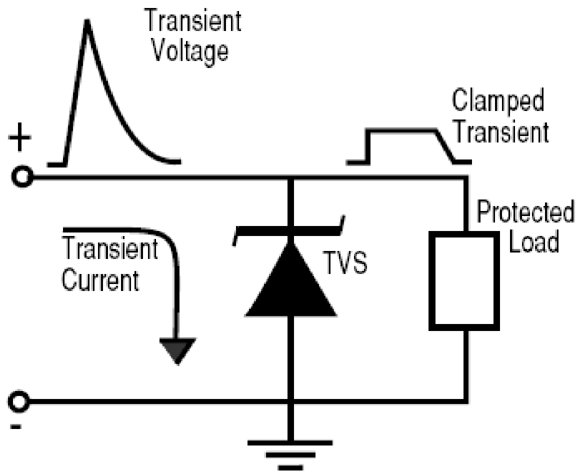


Figure 2-26: Clamped Transient

2.8.4 TVS Protection Options

TVS devices can be categorized as a cable, crowbar, clamping or filter device. Figure 2-27 provides a schematic representation of the TVS devices [25].

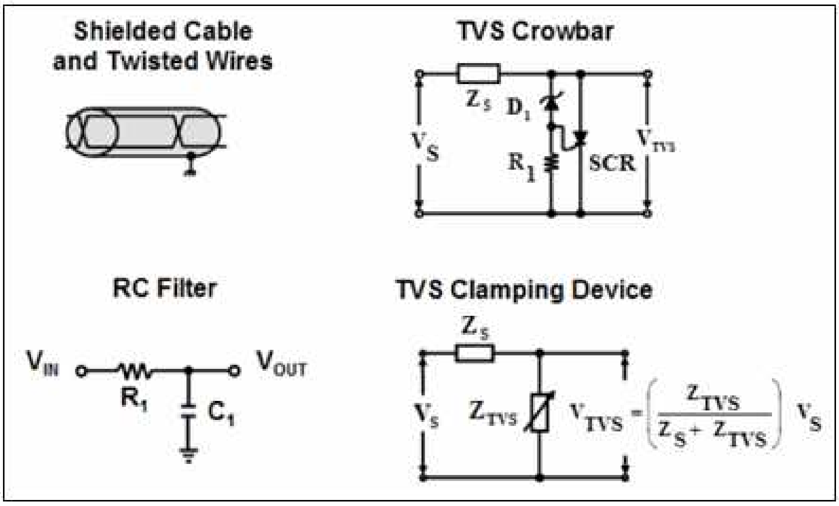


Figure 2-27: TVS Protection Devices

Each TVS option has unique advantages and disadvantages that are summarized in Table 2.2. Many systems use a combination of TVS devices to create a protection circuit that combines the advantages of the different TVS options [25].

Table 2.2: Attributes of TVS Protection Devices

Device	Advantages	Disadvantages
Shielded Cable and Twisted Wires	• Increase RF Immunity • Decrease Emissions	• Cost • Capacitance Increases
Crowbars	• High Power Rating • Shunt Surge Current to GND	• Do Not Absorb Energy • Difficult to Turn "Off"
Filters	• Continuous Noise Filtering • Attenuate Surge Voltage	• Do Not Clamp Surges • May Distort Data Line Signal
TVS Clamping Devices	• Clamp Surge Voltage • Fast Turn−On Time (< 1.0 ns)	• Limited Power Rating • Power Rating & Capacitance

2.8.4.1 Shielded Cable and Twisted Wire Pairs

Figure 2-28 provides an example of a communication system that uses a shielded cable with a twisted wire pair. A shield is an effective tool to prevent EMI problems that arise when the wires connecting multiple electronic modules are exposed to a high noise environment. Shielded cables prevent radiated RF interference from introducing a noise voltage on the signal wires. A shield also reduces the RF noise that a cable emits [25].

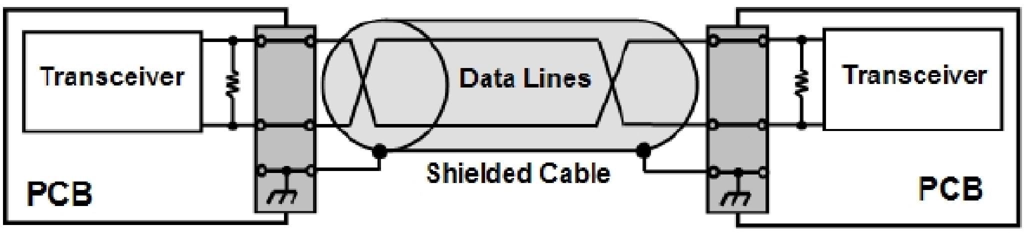


Figure 2-28: Shielded Cable with Twisted Wire Pairs

2.8.4.2 Crowbar TVS Devices

Spark gaps, gas discharge tubes (GDTs), thyristors and thyristor surge protective devices (TSPDs) are TVS devices that are capable of attenuating very large surge currents. When these devices are switched “ON”, the protected circuit is connected to ground through a very low impedance switch. The energy of the transient event must be absorbed by either the source or line impedance and the circuit will not be functional while the TVS device is “ON”. Crowbars are difficult to turn “OFF” and often require an additional commutation circuit, especially in a DC system. Figure 2-29 shows a schematic representation of the crowbar devices [25].

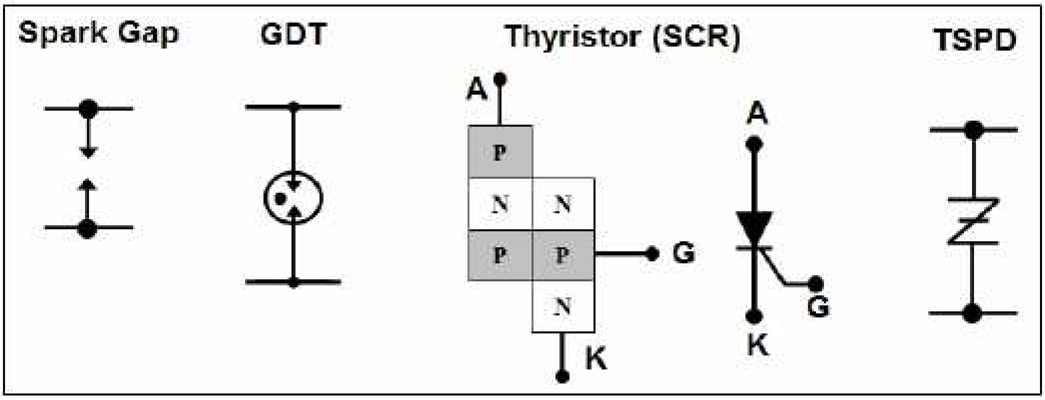


Figure 2-29: Examples of TVS Crowbar Devices

2.8.4.3 Filter TVS Circuits

EMI filter TVS devices are available in a number of options. The most popular configuration is a low pass filter. A low pass filter attenuates the magnitude of a surge pulse by limiting the slew rate of the signal. Filters do not clamp the voltage; thus, it typically is necessary to add a clamping device such as an avalanche TVS diode to ensure that the maximum voltage rating of the protected circuit is not exceeded. The main advantage of filters is that they reduce noise signals during the normal operation of the system. In contrast, crowbar and clamping devices are activated only during the transient event [25].

Figure 2-30 provides examples of several common TVS filter device options [25].

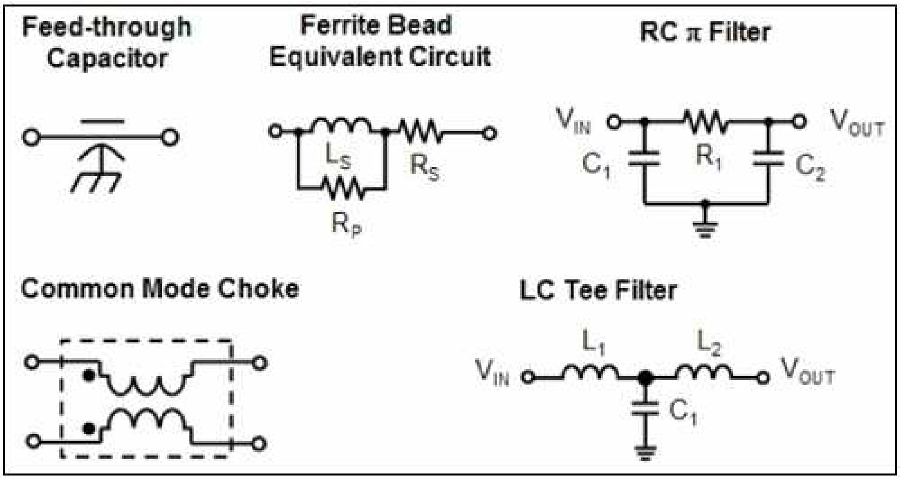


Figure 2-30: Examples of EMI Filter Devices

2.8.4.4 Voltage Clamping TVS Devices

Metal oxide varistors (MOVs), polymers, Zener diodes and TVS avalanche diodes are popular voltage clamping TVS devices. Clamping devices dynamically adjust their impedance in order to maintain a constant voltage. At low voltages below their breakdown voltage, they can be modeled as a very large resistance in parallel with a capacitance. If the surge voltage exceeds the breakdown voltage, the resistance of the device decreases in order to maintain a constant clamping voltage. Figure 2-31 shows a schematic representation of the voltage clamping TVS device [25].

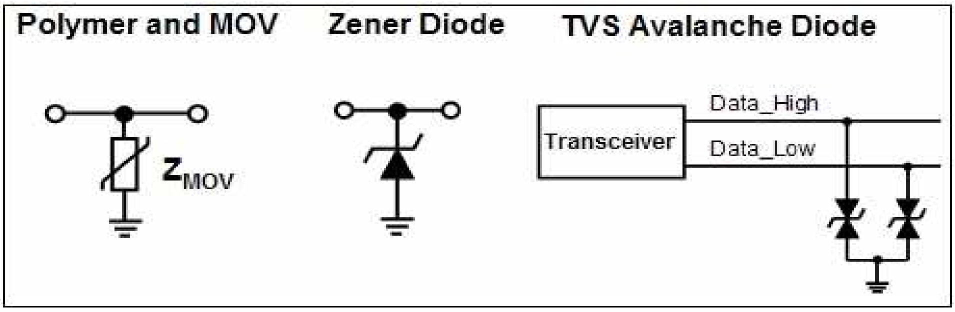


Figure 2-31: Examples of a Voltage Clamping TVS Device

2.8.4.5 Multiple Protection Device Solutions

Figure 2-32 provides a design example that uses multiple TVS devices to provide EMI protection. A shielded cable with twisted wire pairs minimizes the noise voltage induced on data lines. The filter connector serves to attenuate the noise before the signal enters the PCB. Next, TVS diodes, LC filters and a common mode choke are used on the PCB. The TVS diodes provide the overvoltage protection to ensure that a surge voltage is clamped to a safe value. The choke increases the transceiver's CMRR and functions as an effective device to provide filtering without distorting the differential signal. Finally, the capacitors located before and after the choke are used to increase the modules RF susceptibility immunity and lower the noise emitted from the PCB [25].

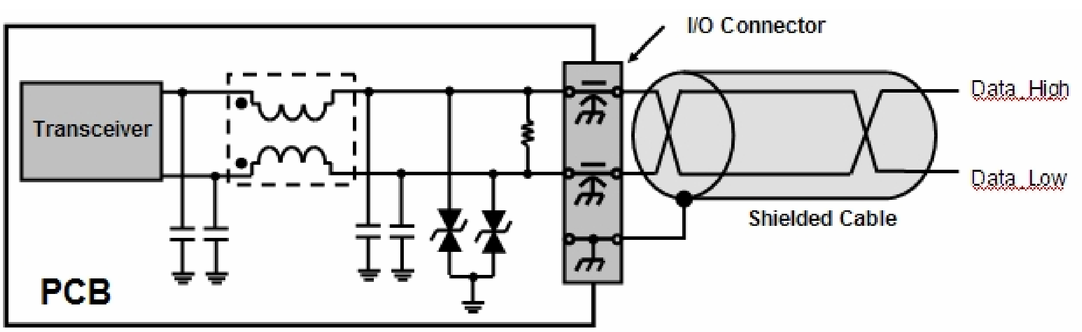


Figure 2-32 : Multiple TVS Device Solution

2.8.5 TVS Selection Guidelines

- Select a device with a working voltage that is greater than the maximum bus voltage.
- Select a device with a clamping voltage less than the maximum specified surge voltage for the protected circuit.
- A bidirectional TVS device may be required for differential amplifier circuits with a common mode offset voltage requirement. The common voltage specification is required when there is a significant difference in the voltage potential between the ground reference of the transmitting and receiving nodes.
- Choose a TVS device that is capable of dissipating the energy of the surge pulse.
- The power rating of most TVS devices decreases with temperature and a derating of the TVS's energy specification maybe necessary.
- The capacitance of the TVS device should be minimized for high speed circuits. [25]

2.8.6 PCB Layout Recommendations

The PCB layout is critical to maximize the effectiveness of a TVS protection circuit.

- Locate the protection devices close to the I/O connector. This allows the devices to absorb the energy of the transient voltage before it can be coupled into the adjacent traces on the PCB.
- Minimize the loop area for the high−speed data lines, as well as the power and ground lines to reduce the radiated emissions and the susceptibility to RF noise.

- Use ground planes to reduce the parasitic capacitance and inductance of the PCB. [25]

2.9 EMI Filtering

When conducted interference on lines entering or exiting an equipment housing must be suppressed, lowpass filters are most commonly used to provide the required suppression. There are a number of basic designs of common (line-to-ground) or differential (line-to-line) filtering for power and signal lines. Variations on these basic designs are many but the basic characteristics are similar and are examined here, to facilitate filter selection for a spesific task [8].

Lowpass EMI filters use passive components – inductors and capacitors. They are the building blocks of Chebysev (high passband ripple and fast increase in insertion loss from cut-off frequency) and Butterworth (low passband ripple and slower insertion loss increase after the cut-off frequency) filter networks. They can also be used individually as lowpass filters as shown in Figure 2-33 [8].

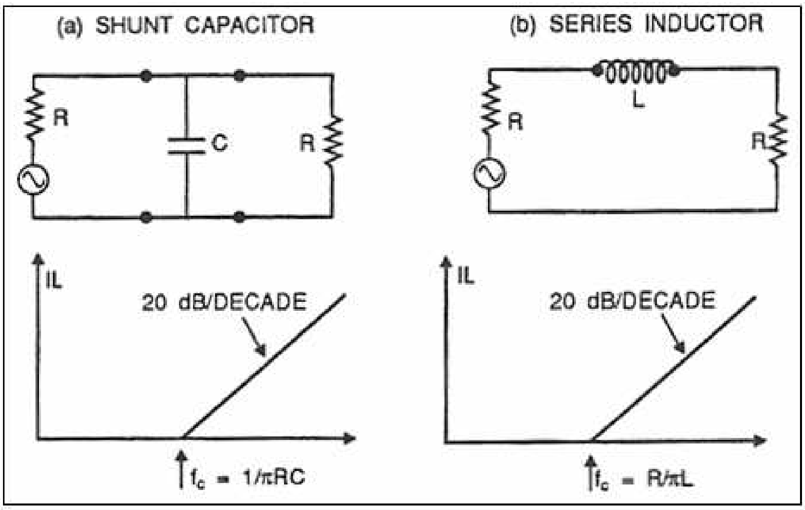


Figure 2-33: Single Element Low pass Filters

When a single element inductor or capacitor does not provide the required filtering, a more powerful filter can be constructed by adding elements to form lowpass filters of the “L”, “T”, or “π” configurations which are most commonly used in EMC design [8] (See Figure 2-34).

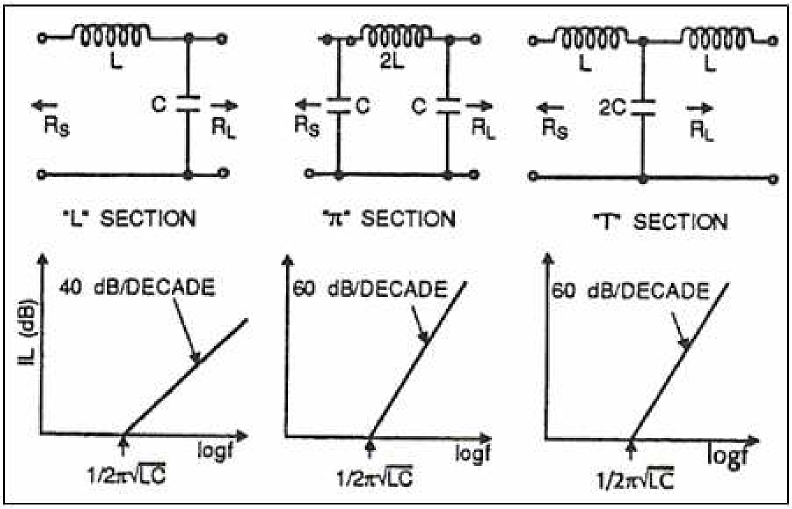


Figure 2-34: Basic L-C Low pass Filters

2.9.1 Attenuating Common Mode EMI

Common mode EMI is usually reduced using a pair of coupled inductors called common mode choke and two capacitors from each line to earth (see Figure 2-35). In this arrangement, the high impedance of the inductor at high frequencies is used to block the exit of EMI currents to the EMI victim [18].

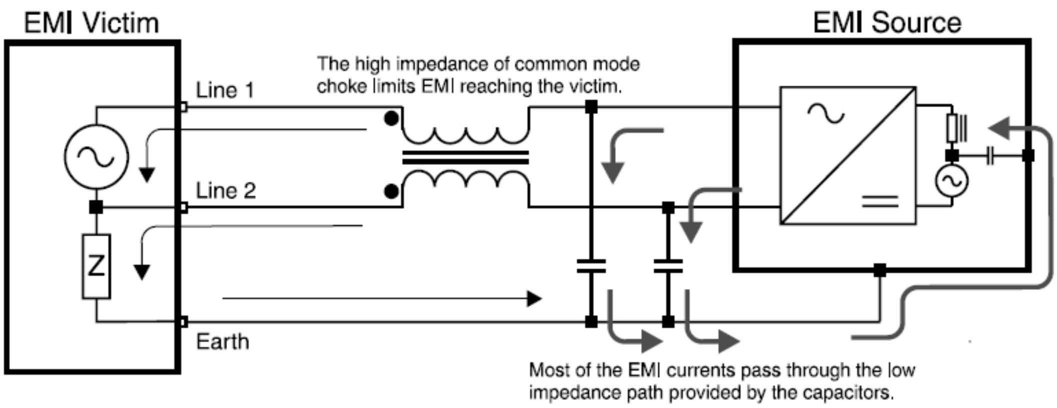


Figure 2-35: Reduction of Common Mode EMI

2.9.2 Attenuating Differential Mode EMI

The same filter shown in Figure 2-35 already has a limited ability to reduce differential mode EMI. Further reduction is achieved by adding a capacitor across the lines (see Figure 2-36). The additional capacitor diverts additional EMI current away from the EMI victim [18].

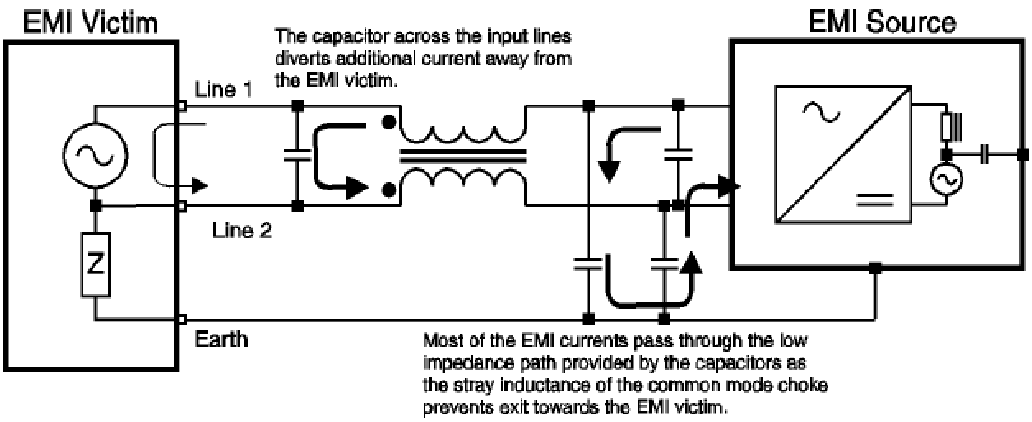


Figure 2-36: Reduction of Differential Mode EMI

2.9.3 Multi-stage Filters

Sometimes the EMI generated by devices such as switching power supplies are so strong that single stage filters described previously will not suffice. In this case, a combination of several LC networks called multi-stage filter is necessary. Figure 2-37 shows a 2-stage filter arrangement. In this example, Stage 2 has an additional pair of separate inductors called differential choke designed to reduce differential mode EMI reaching the EMI victim [18].

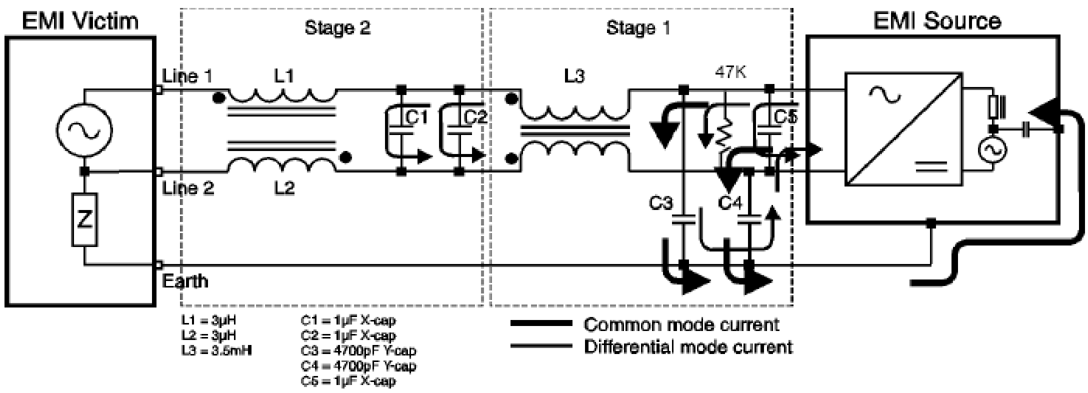


Figure 2-37: Reduction of Both Common and Differential Mode EMI

2.9.4 Filter Components

An EMI filter is essentially an inductor-capacitor (LC) network designed to attenuate high frequency interference while at the same time allow the low frequency operating current to pass through unaffected. The filtering action comes from the impedance characteristics of the inductor and capacitor. The impedance of an inductor increases with frequency; while the impedance of a capacitor decreases as frequency increases. It is important to note that the basic approach to EMI filtering is to use a combination of inductors and capacitors to divert the flow of EMI currents away from the victim [18].

2.9.4.1 Class X&Y Capacitors

Filtering common mode EMI requires capacitors to earth. These capacitors are classified as Y capacitors and safety regulations limit these capacitors to relatively low values [18].

Class Y capacitors are capacitors of enhanced electrical and mechanical reliability and limited capacitance. The enhanced electrical and mechanical reliability are intended to eliminate short-circuits in the capacitor. Limitation of the capacitance is intended to reduce the current passing through the capacitor when AC voltage is applied and to reduce the energy content of the capacitor to a limit that is not dangerous when DC voltage is applied [28].

Differential mode filtering requires capacitors across the input lines. These capacitors are classified as X capacitors [21].

Class X capacitors (X capacitors for short) are capacitors with an unlimited capacitance for use where their failure due to a short-circuit would not lead to the danger of an electric shock [29].

2.9.4.2 Common Mode Choke

Common mode choke coils are used to suppress common mode noise. This type of coil is produced by winding the signal or supply wires one ferrite core [30].

Since magnetic flux flows inside the ferrite core, common mode choke coils work as an inductor against common mode current. Accordingly, using a common mode choke coil provides larger impedance against common mode current and is more effective for common mode noise suppression than using several normal inductors [30] (see Figure 2-38).

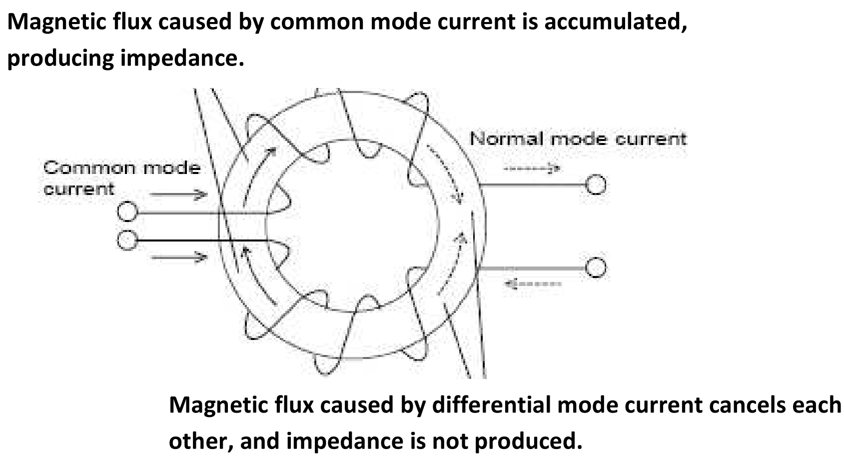


Figure 2-38: Common Mode Choke

Since magnetic flux cancels out inside the ferrite core, impedance is not produced for differential mode current. The magnetic saturation problem is small. Common mode choke coils are suited for common mode noise suppression on lines with large current flow [30].

The differential-mode current, flowing in opposite directions through the choke windings, creates equal and opposite magnetic fields which cancel each other out (see Figure 2-39). This results in the choke presenting zero impedance to the differential mode signal, which passes through the choke unattenuated [20].

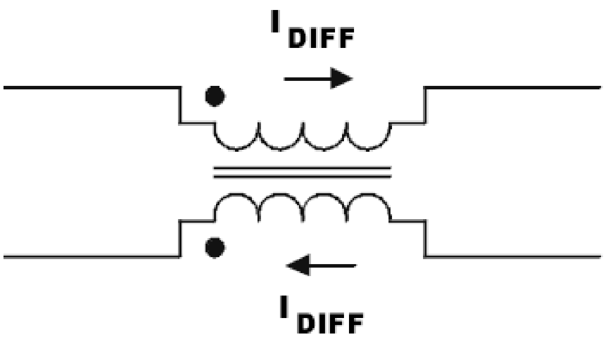


Figure 2-39: Differential Mode Current on a Choke

The common mode current, flowing in the same direction through each of the choke windings, creates equal and in-phase magnetic fields which add together (see Figure 2-40). This results in the choke presenting a high impedance to the common mode signal, which passes through the choke heavily attenuated. The actual attenuation (or common mode rejection) depends on the relative magnitudes of the choke impedance and the load impedance [20].

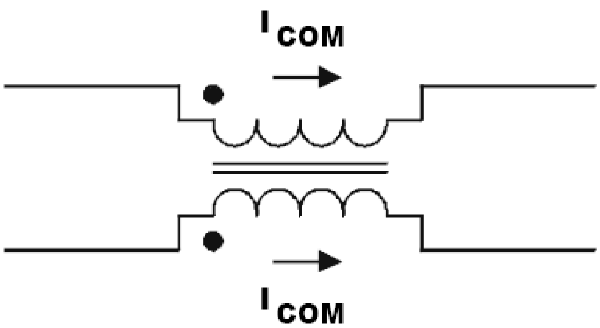


Figure 2-40: Common Mode Current on a Choke

2.9.4.3 Lossy Filters

Instead of trying to block the interference current with a series inductor or short it to ground with a parallel capacitor, the high frequency noise can be dissipated as heat in a resistor [8].

If a resistor can be found that is frequency selective (performs as aseries short or parallel insulator at low frequencies and as a high series resistor or low shunt [parallel] resistor at high frequencies), that property can be used for high frequency EMI control. Lossy line filters are coaxial cables which have a dielectric with a high loss factor at high frequencies. A frequency selective resistor is inserted in parallel to the line, as described in Figure 2-41 [8].

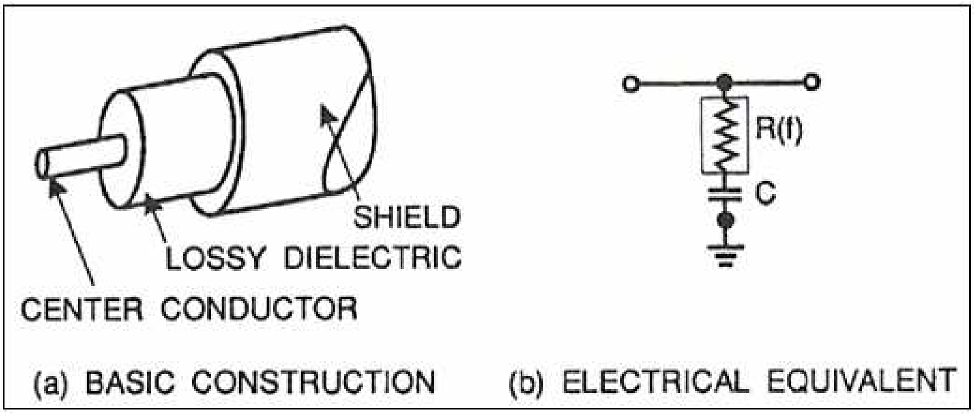


Figure 2-41: Lossy Line Filter Cable

2.9.4.4 Ferrites

A component which provides a series frequency dependent resistor is the ferrite [8].

Ferrites come in a variety of materials and shapes. The materials determine the frequency range, loss factor and saturation. The shape affects the expected suppression and the saturation field. The most commonly used shape is the bead, illustrated in Figure 2-42 [8].

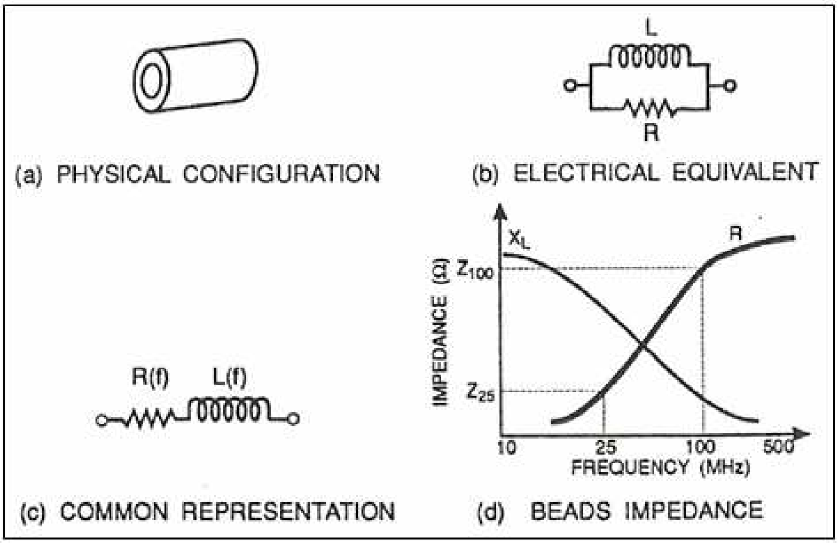


Figure 2-42: The Ferrite Bead

2.10 Understanding EMC Standards and Specifications

2.10.1 Interference Protection Standards

Until recently most countries have had their own regulations and standards governing electro-magnetic interference (EMI) or radio frequency interference (RFI). However, on the 1st of January 1992, the European Directive 89/336/EMC on electro-magnetic compatibility (EMC) came into force. This directive brings a common approach to EMC to every member state of the European Union [31] (see Figure 2-43).

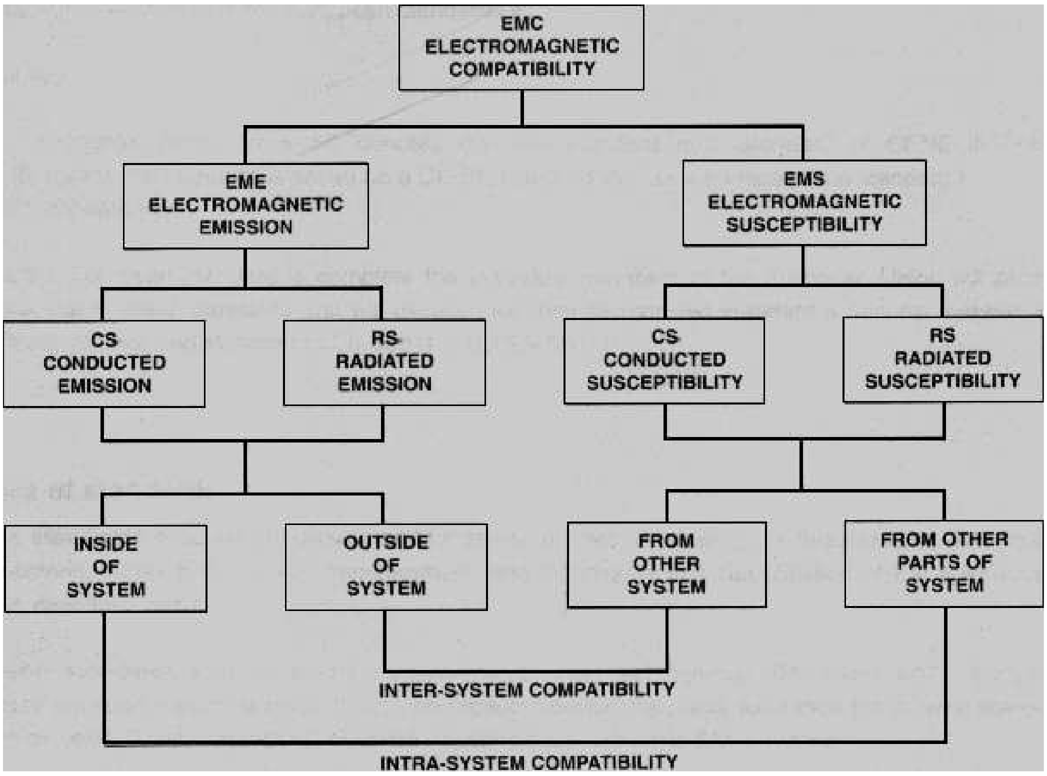


Figure 2-43: EMC Concept

2.10.2 Types of Standards

Basic standards describe the general and fundamental rules for meeting the requirements. Terminology, phenomena, compatibility levels, measurement, test techniques and classification of EM environments are so described within [31].

Generic standards refer to specific environments. They set minimal EMI levels which equipment in these environments must meet. Where no product standards exist then the generic standards are to be used. Generic standards describe household and industrial EMI environments [31].

Products standards are for specific products or product groups. These standards are coordinated with the generic standards [31].

2.10.3 EN 61326 Standard

EN 61326 : Electrical equipment for measurement, control and laboratory use – EMC requirements

This standard defines the EMC requirements for electrical equipment for measurement, control and laboratory use. It specifies the minimum EMC requirements for electrical equipment intended for professional, industrial processes and educational use operating from a supply of less than 1000 V a.c. or 1500 V d.c. [32].

Equipments given below are under the scope of this standard :

a. Electrical Measurement and Test Equipments

These are equipments which measure, show and record one or more electrical or non-electrical quantities and also which do not make measurements like signal generators, measurement apparatus, power supplies and transformers.

b. Electrical Control Equipments

These are equipments which control one or more output quantities according to input variables set before, set locally or set by a remote controller.

These equipments are the İndustrial Process Measurement And Control devices given below :

- process controller devices and regulators,
- programmable control devices,
- power supply units of equipment and systems,
- analog-digital indicators and recorders, etc.
- process measurement,
- converters, positioners, etc. [32]

2.10.3.1 Immunity Requirements

EN 61326 addresses to the standards listed in Table2.7 for immunity requirements.

Table 2.3: EN 61326 Immunity Requirements

STANDARD NO	NAME
IEC 61000-4-2	Electromagnetic compatibility (EMC) –Part 4-2 : Testing and measurement techniques – Electrostatic discharge immunity test
IEC 61000-4-3	Electromagnetic compatibility (EMC) –Part 4-3: Testing and measurement techniques-Radiated,radio-frequency ,electromagnetic field immunity test
IEC 61000-4-4	Electromagnetic compatibility (EMC) –Part 4 : Testing and measurement techniques – Section 4: Electrical fast transient/burst immunity test. Basic EMC Publication
IEC 61000-4-5	Electromagnetic compatibility (EMC)- Part 4-5: Testing and measurement techniques – Surge immunity test
IEC 61000-4-6	Electromagnetic compatibility (EMC) –Part 4-6 : Testing and measurement techniques – Immunity to conducted disturbances, induced by radio-frequency fields
IEC 61000-4-8	Electromagnetic compatibility (EMC) – Part 4-8: Testing and measurement techniques – Power frequency magnetic field immunity test

2.10.3.2 Performance Criteria For Immunity

- *Requirements for Performance Criterion A:* The EUT shall continue to operate as intended. No degradation of performance or loss of function is allowed below a performance level specified by the manufacturer, when the EUT is used as intended [32].
- *Requirements for Performance Criterion B:* The EUT shall continue to operate as intended after the test. No degradation of performance or

loss of function is allowed below a performance level specified by the manufacturer, when the EUT is used as intended. During the test, degradation of performance is however allowed. No change of actual operating state or stored data is allowed [32].

- *Requirements for Performance Criterion C:* Temporary loss of function is allowed, provided the function is self recoverable or can be restored by the operation of the controls [32].
- *Performance Criterion D:* Damage of equipment.

2.10.3.3 Emission Requirements

EN 61326 addresses to the standards listed in Table2.8 for emission requirements.

Table 2.4: EN 61326 Emission Requirements

STANDARD NO	NAME
IEC 61000-3-2	Electromagnetic compatibility (EMC) –Part 3-2: Limits – Limits for harmonic current emissions (equipment input current • 16A per phase)
IEC 61000-3-3	Electromagnetic compatibility (EMC) – Part 3-3: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low – voltage supply systems, for equipment with rated current • 16 A per phase and not subject to conditional connection
CISPR 11	Industrial, scientific and medical (ISM) radio-frequency equipment – Electromagnetic disturbance characteristics – Limits and methods of measurement
CISPR 14	Limits and methods of measurement of radio disturbance characteristics of electrical motor – operated ve thermal appliances for household and similar purposes, electric tools and electric apparatus
CISPR 16-1	Specification for radio disturbance and immunity measuring apparatus and methods
CISPR 16-2	Specification for radio disturbance and immunity measuring apparatus and methods
CISPR 22	Limits and methods of measurement of radio disturbance characteristics of information technology equipment

CHAPTER 3

EMC ASPECTS OF ELECTRIC POWER QUALITY MONITOR

3.1 System Description

Electric Power Quality Monitor (See Figure 3-1) is a measurement device that makes power quality measurements according to EN 50160 and IEC 61000-4-30 and stores the measured data, then transfers this data to Power Quality Center through various network structures.

Figure 3-1: Electric Power Quality Monitor

Power quality monitors are being developed as a subproject in National Power Quality Project. Within this sub-project, National Power Quality Monitors will be connected to the points selected to be the most critical ones in the Turkish Transmission System, and changes in Power Quality Parameters, and Active and Reactive Power Flows will be monitored from a center as "off-line".

3.2 Technical Specifications

EPQM can take measurements on 2 feeders. There are 12 total input channels as 6 of them are voltage and 6 of them are current inputs. The sampling rate is 25,6 kHz for each channel input.

Case of EPQM is made of steel sheet material and coated with non-conductive material (See Figure 3-2).

A current usually called *enclosure/touch/chassis leakage current* flows from human body to ground on the created inductance as human body touch. This current causes electrical shock on human body. Therefore for safety purposes a grounding screw is located on the power supply input side of EPQM case (See Figure 3-2).

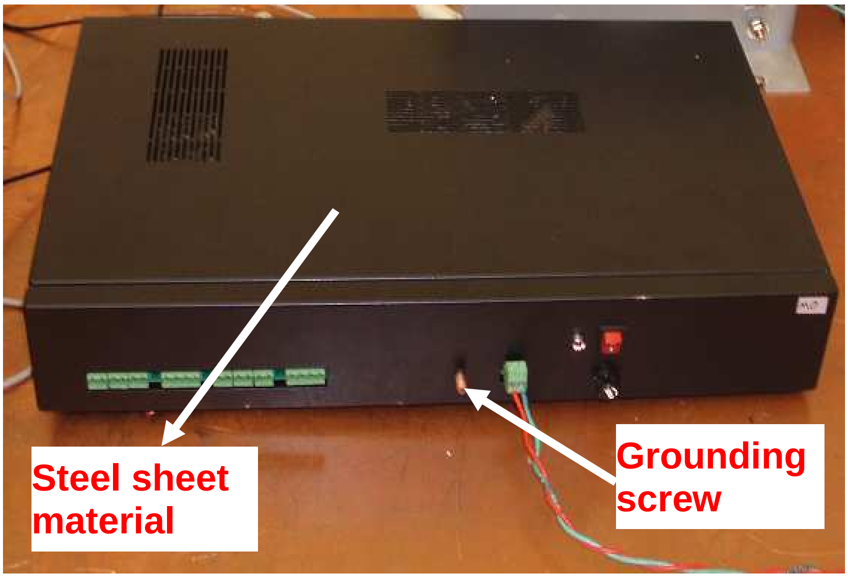


Figure 3-2: Casing of EPQM

Other technical specifications of EPQM are given in Table 3.1.

Table 3.1: Technical specifications of EPQM

Maximum voltage input level	:	AC 100 rms, 45 Hz-65 Hz
Maximum current input level	:	5A, rms , (with 1/3000 revolution current probe)
Supply input	:	36-72V DC
Network type	:	• RS-232 communication port • Ethernet port (10-100 base TX)

3.3 The Units in EPQM and their EMC Aspects

The units in EPQM are shown in Figure 3-3.

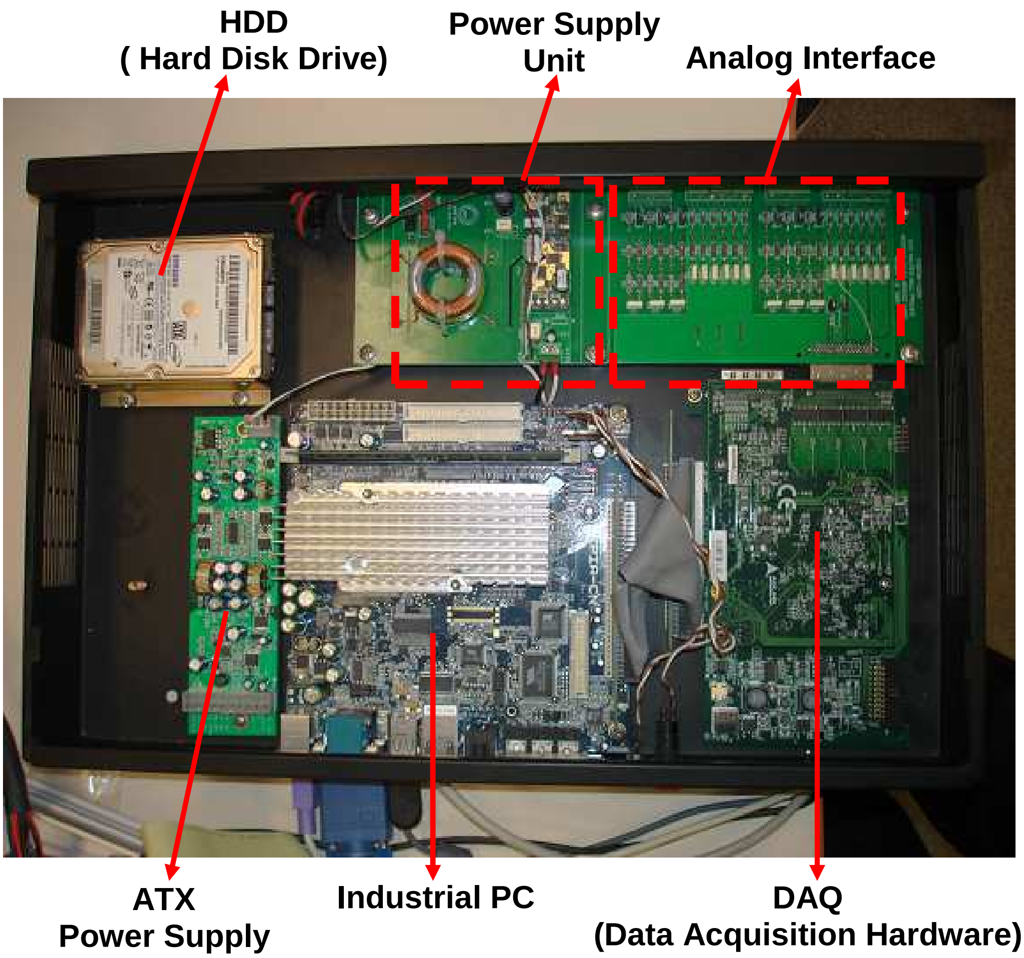


Figure 3-3: The Units Inside EPQM

<u>HDD (Hard Disk Drive) :</u>

GMR recording heads used in today's hard disk drives are very sensitive to damage from impulsive current transients caused by electrostatic discharge (ESD) and even the electromagnetic interference (EMI) due to a nearby ESD event [33, 34, 35, 36].

So if the ESD pulses jump inside or find a way to radiate inside EPQM HDD part can easily be damaged.

HDDs are usually designed as immune to the radiated fields. Their metallic case usually helps the radiated RF immunity of HDDs.

Power Supply Unit :

It is known that conducted emissions are mainly caused by power supplies because of their switching operation. Power supplies affect the radiated emissions too as the conducted emissions of the supply cause radiation from the cables. EMI filtering is a good approach for keeping the conducted and radiated emissions of the power supplies below some limits.

A 48V/12V DC-DC converter with 50 W power capability is used in the power supply unit of EPQM. So this unit is a possible EMI source for conducted and radiation emissions.

In contrast, power supply unit can be influenced by the radiated and conducted RF fields. Proper casing of EPQM can fix possible problems however some countermeasures like shielding the DC-DC converter with EMI protective cover can also be taken.

All electrical circuits can be damaged by ESD. So another possible interference to be influenced is ESD. ESD pulse should not reach this unit too.

ATX Power Supply :

This unit is fed from the “power supply unit” and generates the voltage levels needed by the processor and other components in the industrial PC. So there is no interface of this unit with the power mains. Thus, conducted emissions caused by this unit is internal and not of concern in this study. However, it can still produce radiated fields on its supply input cables. These fields can cause problems in radiated emission tests.

As the power supply unit, this unit can also be influenced by the conducted and radiated RF fields. Similar countermeasures can be taken for this unit too.

Analog Interface :

This unit is the analog interface of EPQM for the voltage and current inputs to be measured. Analog signals are usually influenced by RF fields coupling to the cables or directly to the related PCB sections. Current transducers used in this unit are very sensitive to radiated fields, so it is important to evaluate the performance of this unit for radiated and conducted RF immunity tests.

Usually shielding of the cables or using ferrites on the cables can fix a possible problem.

Industrial PC :

This unit includes a motherboard, a processor and a RAM unit. Processors are usually used for high speed operations. So high frequency noise can fool them sometimes. As ESD is a high frequency pulse, software of EPQM can be effected by ESD. Of course ESD can cause damage to the processor, even to the RAM unit or electrical circuits on motherboard which is a more important case.

Radiated RF field can influence the analog signals in this unit. Proper casing of EPQM should fix the problem.

DAQ (Data Acquisition Hardware) :

This unit samples the analog signals measured by the analog interface circuits. So it is susceptible to radiated RF fields. Again proper casing of EPQM should fix this susceptibility problem.

As in the other units ESD is an enemy of this unit too. ESD should not reach this unit.

EMC aspects of EPQM mentioned up to now are summarized in Table 3.2.

Table 3.2: EMC Aspects of EPQM

	EMISSION		IMMUNITY				
	RADIATED	CONDUCTED	RADIATED RF	CONDUCTED RF	ESD	EFT/BURST	SURGE
HDD	-	-	-	-	+	-	-
POWER SUPPLY UNIT	+	+	+	+	+	+	+
ANALOG INTERFACE	-	-	+	*	+	*	*
ATX POWER SUPPLY	+	**	+	**	+	-	-
INDUCTRIAL PC	-	-	+	*	+	*	*
DAQ	-	-	+	-	+	-	-

+ Applicable

- Not applicable

* For cables longer than 3 meters according to EN 61326

** Internal and not of concern

CHAPTER 4

EMC EMISSION TESTS AND COUNTERMEASURES

4.1 Introduction

EN 61326 standard addresses to IEC 61000-3-2, IEC 61000-3-3, CISPR11, CISPR14, CISPR16-1, CISPR16-2 and CISPR22 emission standards.

IEC 61000-3-2 is applied to the power inputs of the devices which only operates from 50 Hz or 60 Hz and at 220/380 V, 230/400 V, 240/415 V voltage levels.

IEC 61000-3-3 is applied to the power inputs of the devices which only operate from 50 Hz and at a level between 220 V and 250 V.

CISPR14 is an emission standard for electrical toys and hand tools operate from 250 V ac and for other devices operate from 480 V ac.

As EPQM operates from 36-72V DC, these three standards need not be applied.

CISPR16-1 and CISPR16-2 include the specifications for the measuring apparatus used in the tests, not for the EUT.

CISPR22 defines the limits and methods of measurement of radio disturbance characteristics of information technology (IT) equipment.

CISPR11 defines the limits and methods of measurement of electromagnetic disturbance characteristics of Industrial, scientific and medical (ISM) radio-frequency equipment.

EPQM is not an IT equipment, however it is an ISM equipment. So only CISPR11 is to be applied to the EPQM as an emission standard.

Emission requirements for EPQM are summarized in Figure 4-1.

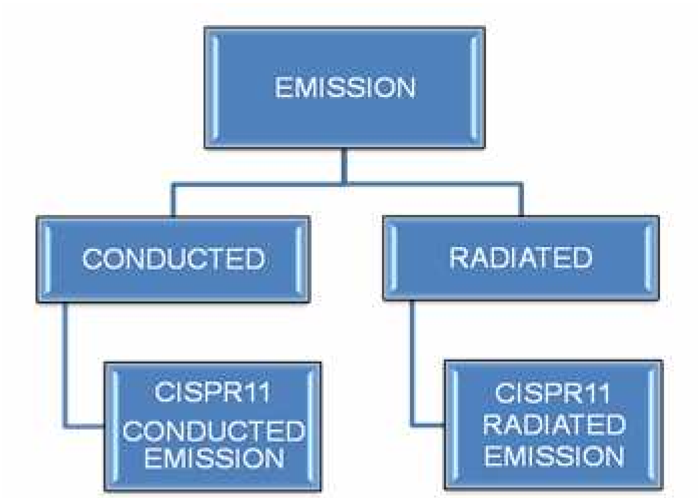


Figure 4-1: EN 61326 Emission Requirements for EPQM

4.2 CISPR 11 Standard

4.2.1 Objective of CISPR 11

CISPR 11 formulates radio-frequency emission requirements and is applicable to apparatus which intentionally generate energy in the ISM frequencies, as designated by ITU. However, the standard is also applicable to all kinds of apparatus, equipment and installations which are intended for use in an industrial environment and for laboratory applications. It includes medical equipment, e.g. for therapeutic purposes. The standard is suitable for “in situ” measurements. Examples are:

- r.f. heating equipment and installations;
- induction cooking appliances;

- microwave ovens and cooking appliances;
- r.f. excited welding equipment;
- spot welders;
- spark erosion equipment;
- microwave therapy equipment;
- ultrasonic equipment;
- medical and industrial X-ray equipment;
- laboratory equipment like
    - oscilloscopes;
    - spectrum analyzers;
    - network and logic analyzers;
    - signal generators;
- stand alone power supplies and power generators [37]

4.2.2 Grouping The Devices

Group 1 Devices:

The devices other than the devices that generate RF energy and use it for material processing or spark processing [37].

Group 2 Devices:

The devices that generate RF energy and use it for material processing or spark processing [37].

4.2.3 Classifying The Devices

Class A Devices:

The devices other than the devices that are directly coupled to the electrical systems of houses or likely places are in this class [37].

Class B Devices:

The devices that are directly coupled to the electrical systems of houses or likely places are in this class [37].

4.2.4 Test Levels

According to the group and class definitions in parts 4.2.2 and 4.2.3, EPQM is “Group 1, Class A” device. The conducted emission test levels for “Group1, Class A” devices are given in Table 4.1.

Table 4.1: CE Limit Levels for Group1,Class A

Frequency band (MHz)	Limit levels for Class A devices dB (µV)	
	Group 1	
	Quasi-peak	Average
0,15 – 0,50	79	66
0,50 – 5	73	60
5 -30	73	60

The radiated emission test levels for “Group1, Class A” devices are given in Table 4.2.

Table 4.2: RE Limit Levels for Group1,Class A

Frequency band (MHz)	Measurement at test area	Measurements at the environment
	Group 1, Class A 10 m measurement distance dB (µV/m)	Group 1, Class A 30 m far from the building that the device will be installed dB (µV/m)
0,15 – 30	-------	-------
30 – 230	40	30
230 – 1000	47	37

4.2.5 The Line Impedance Stabilisation Network (LISN)

A LISN is a device to create a known impedance on power lines of electrical equipment during electromagnetic interference testing. A LISN is typically designed to allow for measurements of the electromagnetic interference existing on the power line [38] (See Figure 4-2).

It fulfills three main functions:

- It filters the mains voltage and should block higher frequencies than the mains frequency.
- It should provide a characteristic impedance to the device under test (EUT).
- The conducted interference voltage produced by the EUT is transferred to a meter, for example a spectrum analyzer or an EMI receiver. [38]

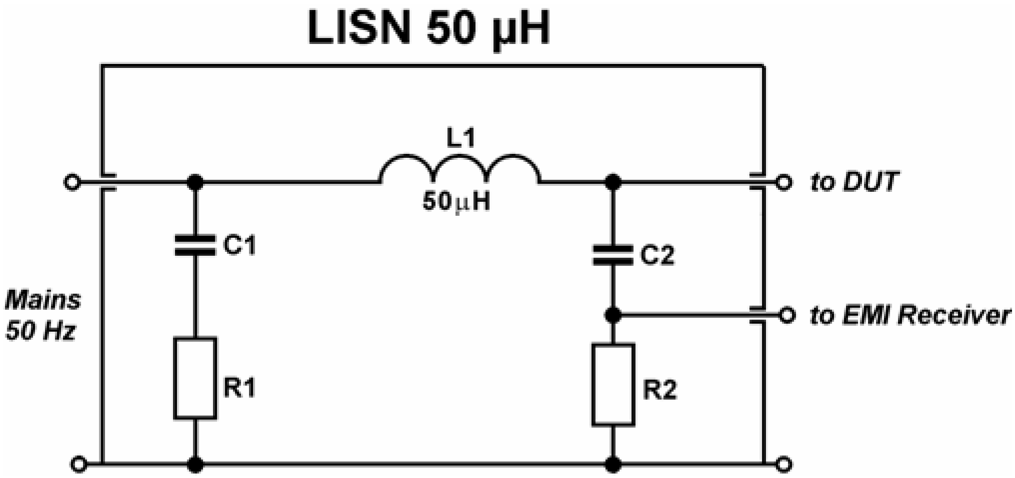


Figure 4-2: LISN Block Diagram

4.3 Conducted Emission Measurements According to CISPR 11

4.3.1 Test Setup

A schematic diagram for a typical CE test setup is shown in Figure 4-3. Conducted emission measurements are done with an average detector, so limit levels given for this kind of detector are used during the tests.

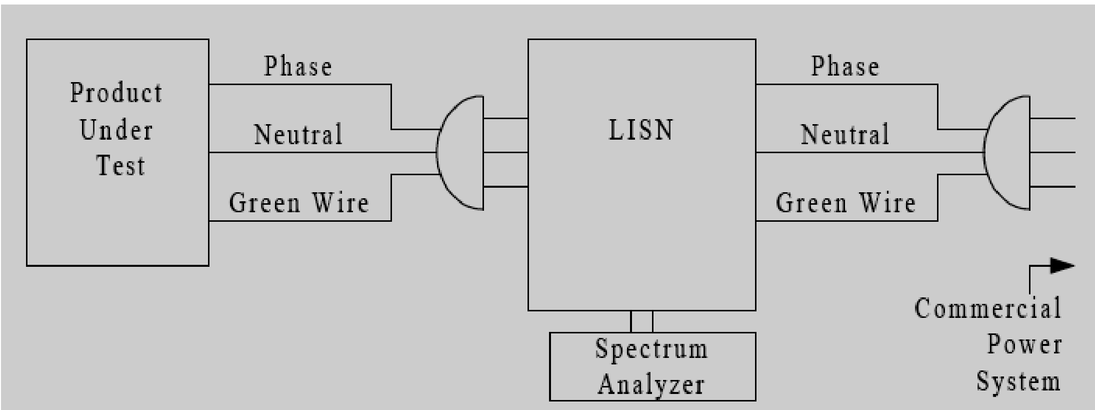


Figure 4-3: A schematic Diagram for a Typical CE Test Setup

CE test configuration for EPQM is shown in Figure 4-4. Average detector is coupled to the LISN on the positive line for the positive line noise measurements and to the LISN on the negative line for negative line noise measurements.

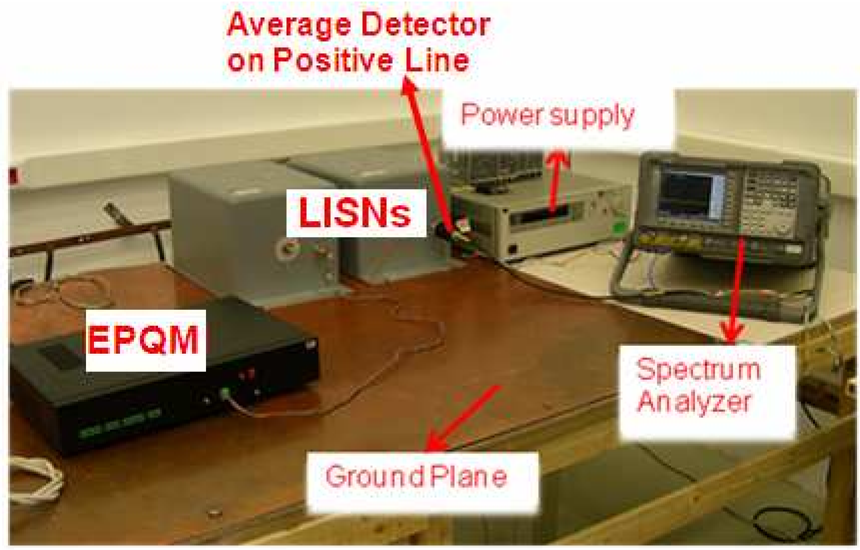


Figure 4-4: CE test configuration for EPQM

4.3.2 Positive Line Measurement

First the ambient noise is measured in order to check whether the circumstances for the conducted emission test are okay. Because in order to get acceptable results, the noise level at each frequency has to be at least 6dB less than the limit levels given by the standard. Measured ambient noise is given in Figure 4-5.

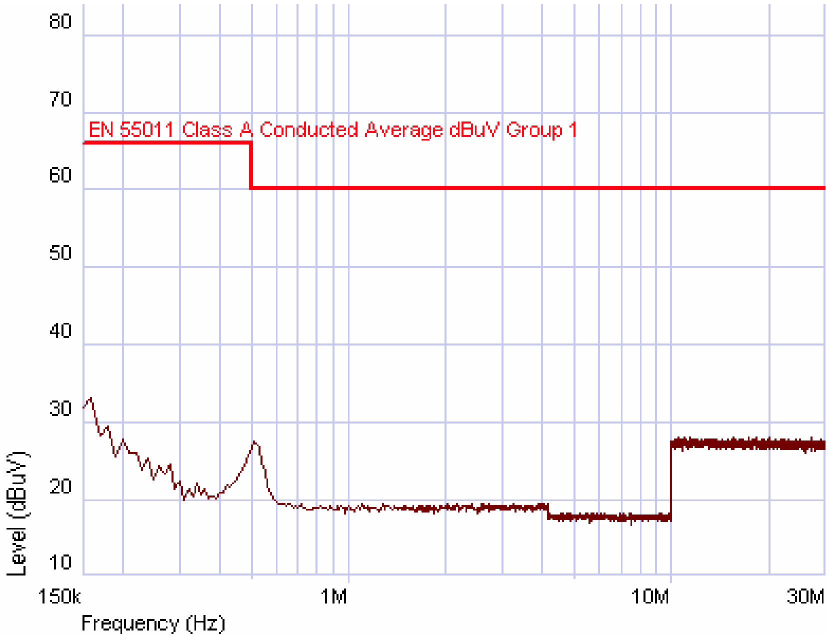


Figure 4-5: Ambient Noise Level on the Positive Line

As the maximum conducted emission level is more than 6dB below the limit levels, it is adequate to take measurements. The EPQM is powered on and the embedded measurement program is run.Then a measurement is taken on the positive line of the EPQM. Figure 4-6 shows the conducted noise level on the positive line caused by the EPQM.

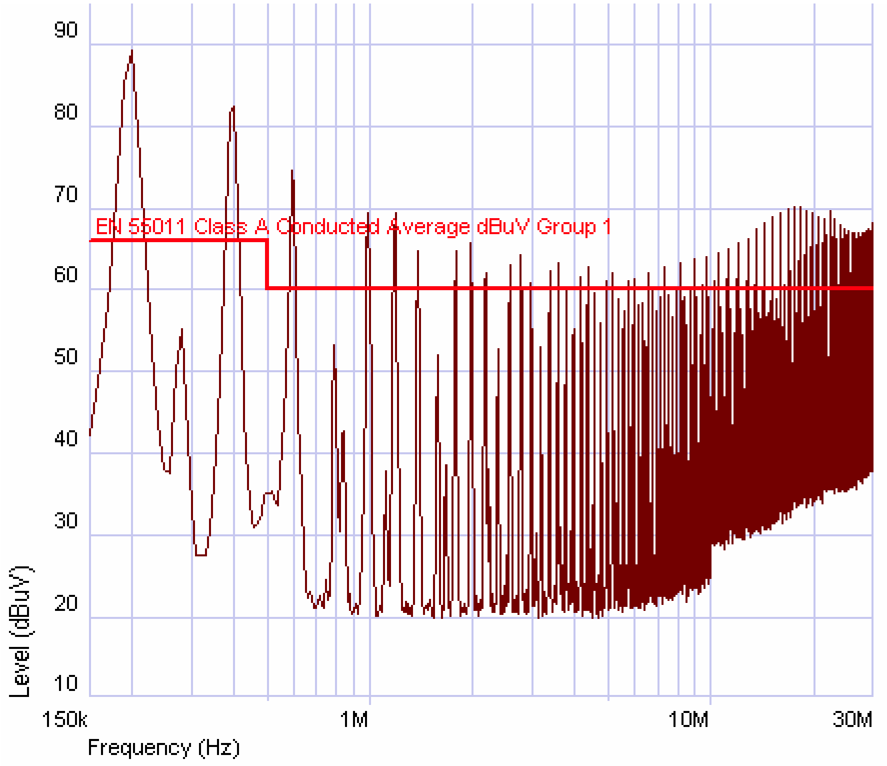


Figure 4-6: EPQM Noise Level on the Positive Line

4.3.3 Negative Line Measurement

First the ambient noise level is measured for the same reason mentioned in the previous part. This measurement result is shown in Figure 4-7.

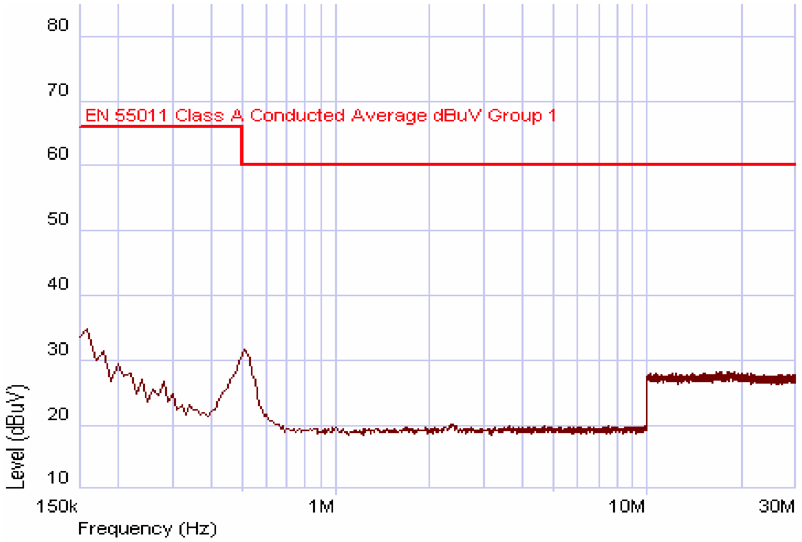


Figure 4-7: Ambient Noise Level on the Negative Line

Then a measurement is taken as the EPQM is operating. Figure 4-8 shows the conducted noise level on the negative line caused by the EPQM.

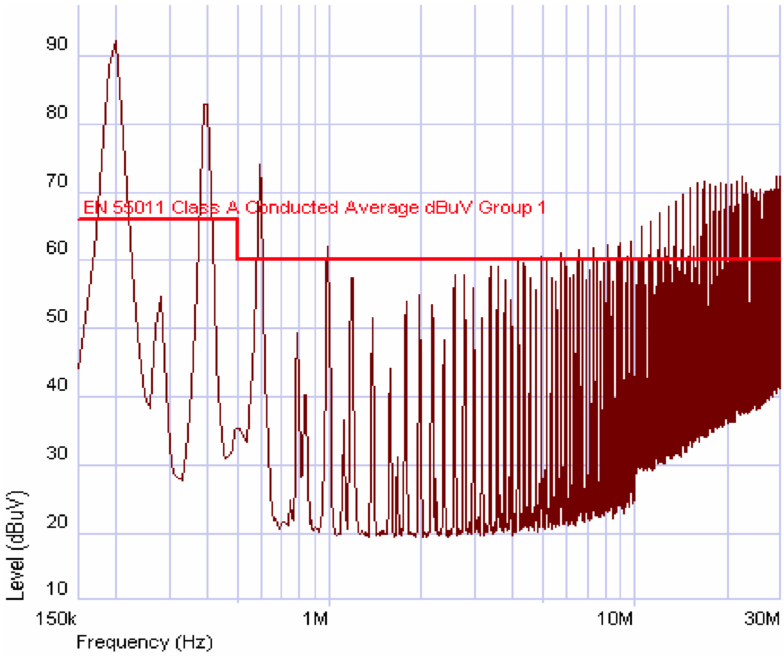


Figure 4-8: EPQM Noise Level on the Negative Line

4.3.4 Results and Discussions

Examining the first three noise levels over the limits (See Figure 4-9), it is seen that 200 kHz is a problematic frequency. The first pulse over the limits is at 200 kHz. Then the second pulse is at 400 kHz and the third at 600 kHz. So it is obvious that these pulses are the second and third harmonics of the pulse at 200 kHz.

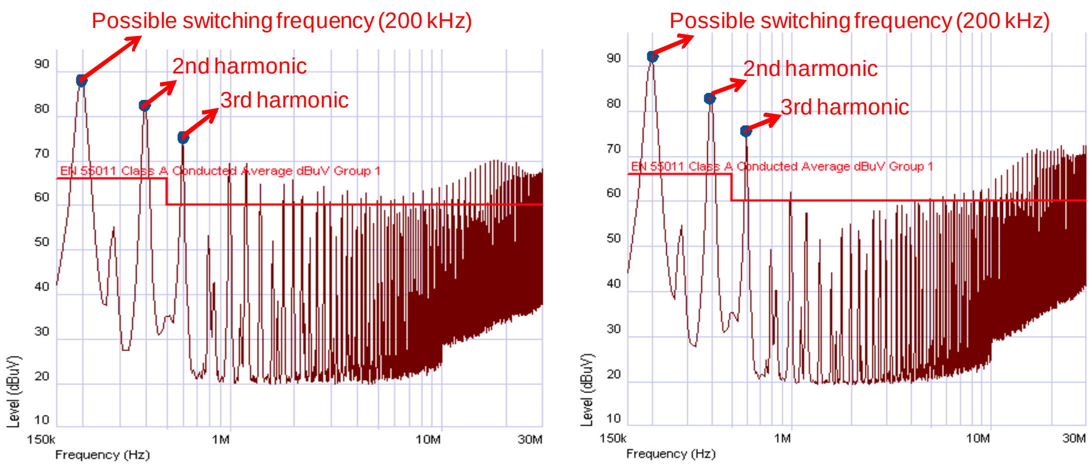


Figure 4-9: Noise levels over the limits

As the test is applied to the supply input of the EPQM, this problem appears to be caused by the DC-DC converter in the supply unit of the EPQM, concerning the fact that today's most DC-DC converters have switching frequencies between 100 kHz – 400 kHz. Also above 10 MHz, the EPQM can not pass the test. So considering both the positive and negative line measurement results, it is obvious that some countermeasures should be taken.

4.4 Conducted EMI Filter Designed for EPQM

4.4.1 Predicting the CM and DM Components

Dealing with conducted EMI has been an important issue for power electronics designers. It's important that, when dealing with the conducted EMI noise, common-mode (CM) and differential-mode (DM) noise must be conserned seperately. As the proposed EMI filter will have both CM-filter and DM-filter components, CM noise and DM noise frequencies have to be predicted.

Due to the explanations of differential and common mode signals at part 2.5.1.1 and part 2.5.1.2, it is obvious that common mode current flows in the same direction at both positive and negative lines as differential mode current flows in the opposite direction as shown in Figure 4-10.

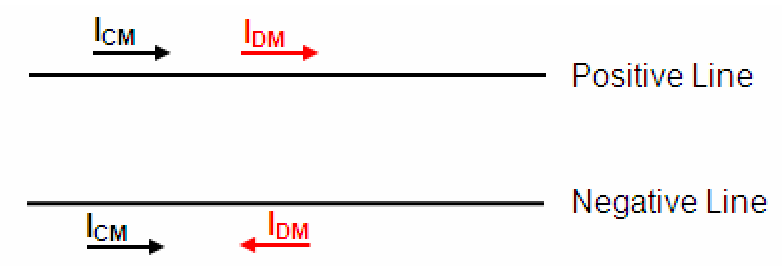


Figure 4-10: Currents on the Positive and Negative Lines

Current probe method can be used to predict the CM and DM components of the noise by taking current measurements on the cables. Current probe method helps us to measure current on a conductor with no direct connection. We are measuring the current and therefore we will have dBµAs instead of dBµVs. As the CE limits in the standard are given in dBuVs, a correction factor of 34 dB has to be added to the observed emission levels according to the Eqn. 4.1 given below:

$$dB\mu A = dB\mu V - 20\log(Zt) = dB\mu V - 34dB \ (Zt = 50\Omega) \qquad \text{(Eqn. 4.1)}$$

Eqn. 4.1 is observed by simply taking the logarithm of $I_{measured} = V/Z_t$ where Zt refers to the impedance of LISN. Zt is assumed to be constant and 50 Ω across the frequency band of concern, and the error caused by the stray capacitance between the current probe and the cable is neglected.

The measurement software is configured for the below measurements.

4.4.1.1 CM Measurement

The total noise on two lines, positive and negative, is measured using the setup shown in Figure 4-11. Test site configuration for this setup is shown in Figure 4-12.

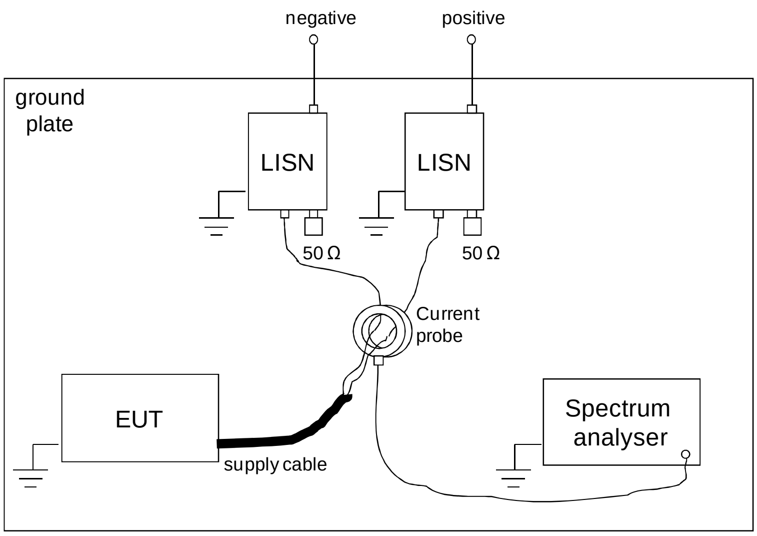


Figure 4-11: CM Measurement Setup

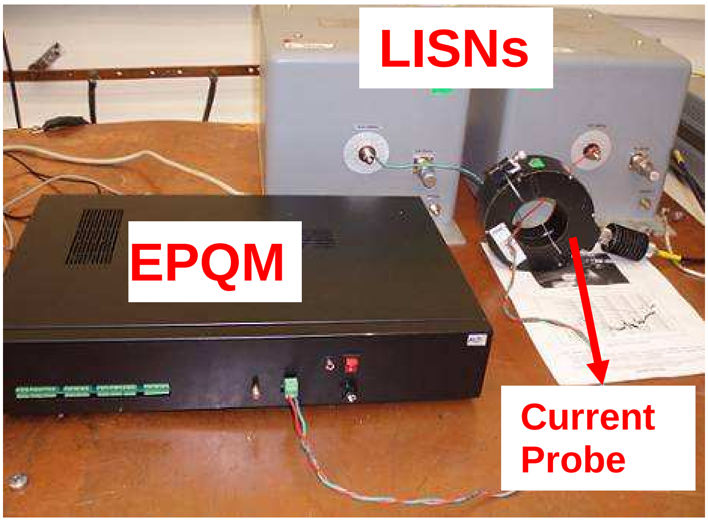


Figure 4-12: CM Measurement on EPQM Power-mains

Measured CM current is shown in Figure 4-13 and can be found by the equation:

$$I_{measured} = I_{positive} + I_{negative} = (I_{CM} + I_{DM}) + (I_{CM} - I_{DM}) = 2I_{CM}$$

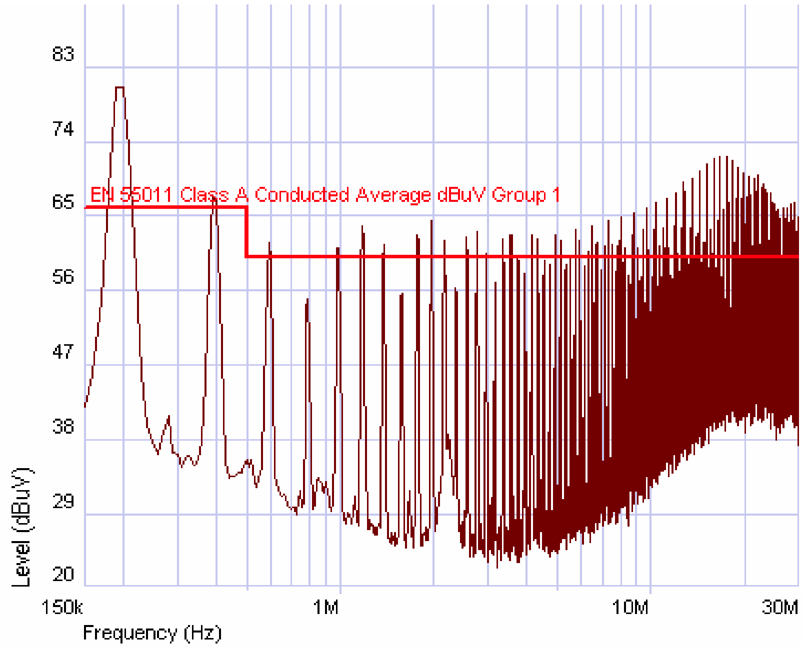


Figure 4-13: Measured CM current

4.4.1.2 DM Measurement

The cable on the negative line is reversed and the measurement is repeated using the setup shown in Figure 4-14. Test site configuration is shown in Figure 4-15.

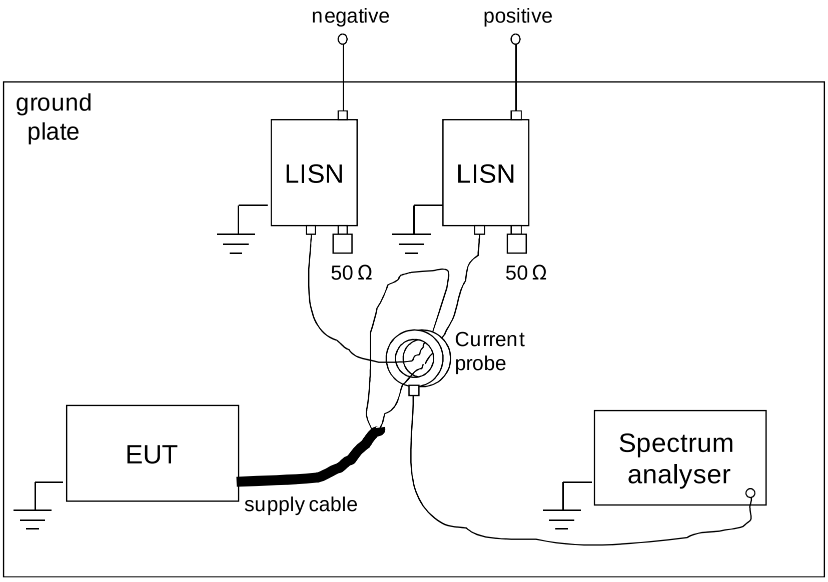


Figure 4-14: DM Measurement Setup

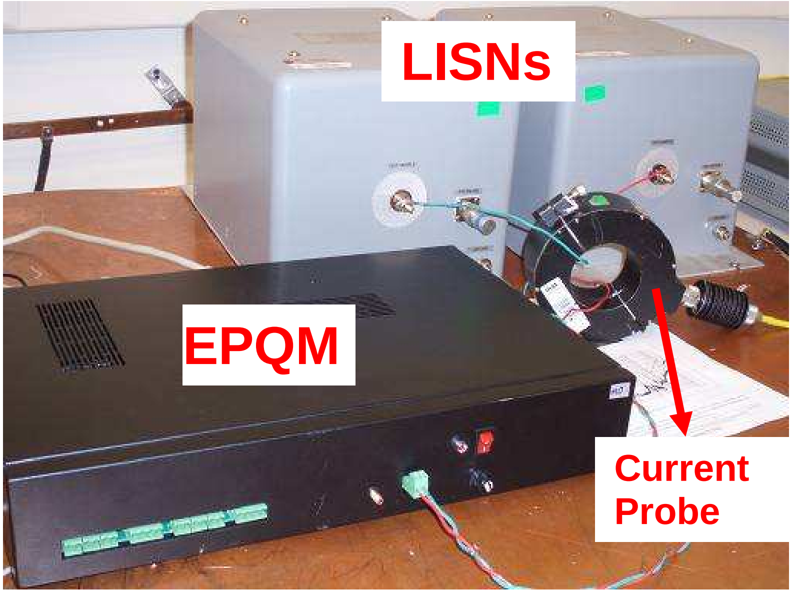


Figure 4-15: DM Measurement on EPQM Power-mains

Measured CM current is shown in Figure 4-16 and can be found by the equation:

$$I_{measured} = I_{positive} - I_{negative} = (I_{CM} + I_{DM}) - (I_{CM} - I_{DM}) = 2I_{DM}$$

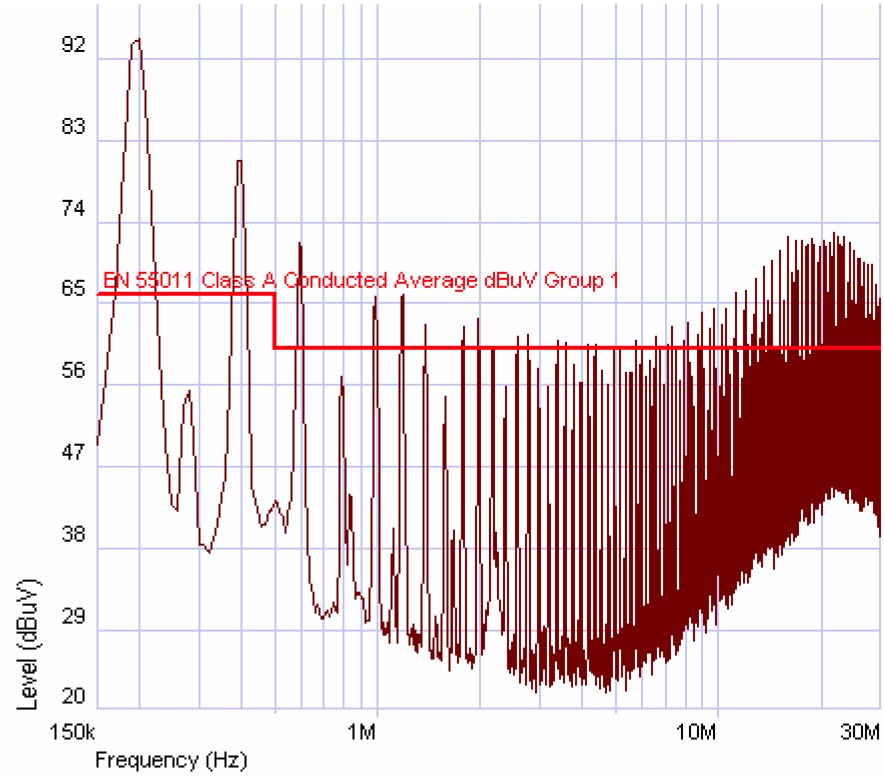


Figure 4-16: Measured DM current

4.4.2 Required Attenuation Calculation

The observed data for both CM and DM measurements is compared with specified CE limit. The attenuation requirement for a filter is found by subtracting the limit level specified in the standard from the observed emission levels:

$$Required\ attenuation(dB) = Emission\ observed(in\ dB) - Limit(dB)$$

Before calculating the required attenuation, 6 dB is subtracted from each of the emission levels observed in part 4.4.1.1 and part 4.4.1.2. Because the CM and DM noise measurements with the setups shown in Figures 4-11 and 4-14 gives us twice the level of CM noise current (I_{CM}), and DM noise current (I_{DM}). Subtracting 6dB means halving the signal level.

Figure 4-17 shows the required attenuation for CM noise, and Figure 4-18 shows the required attenuation for DM noise, drawn by the help of Matlab's functions.

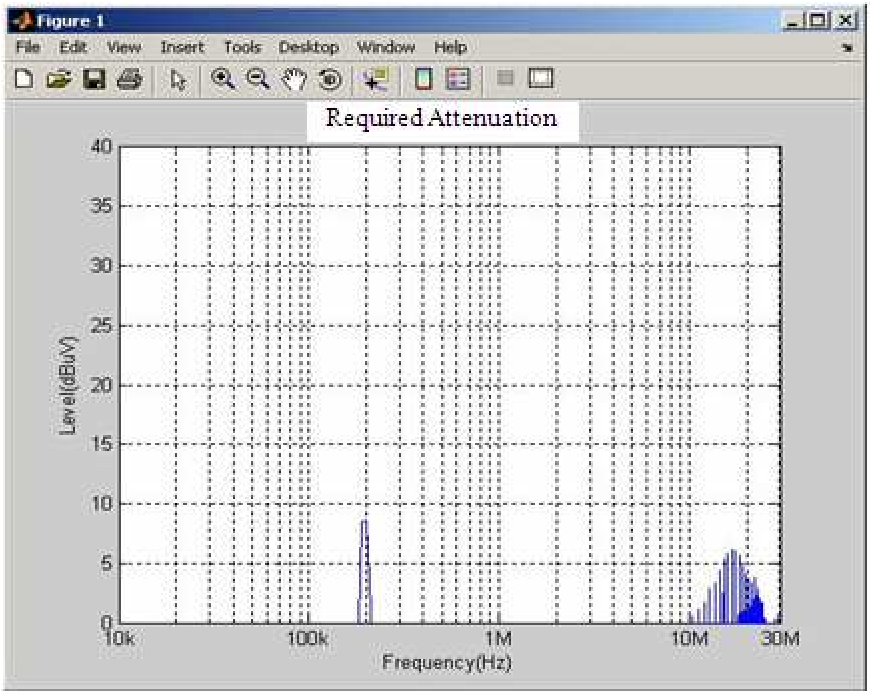


Figure 4-17: Required CM attenuation

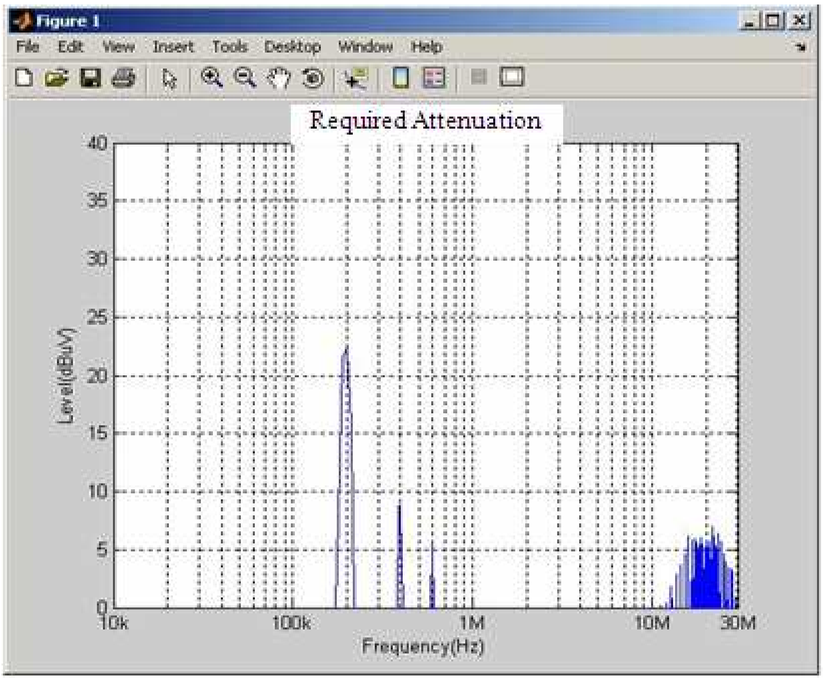


Figure 4-18: Required DM attenuation

4.4.3 Filter Design

4.4.3.1 Design Procedure

A filter for suppressing the conducted noise is given in Figure 4-19. This filter suppresses both differential-mode (DM) and common-mode (CM) noise [39].

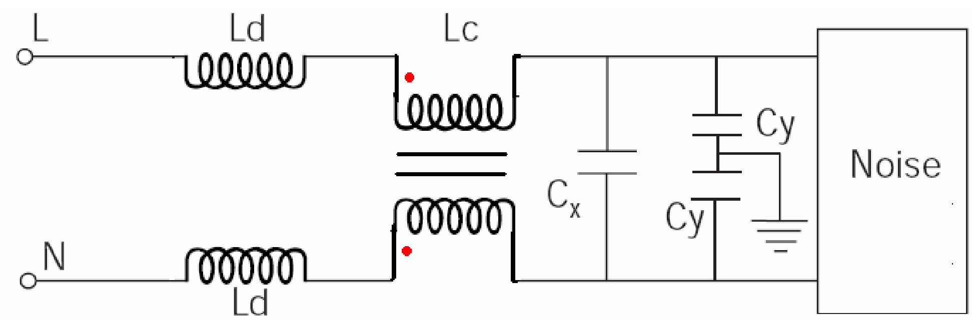


Figure 4-19: Typical EMI filter

Filter shown in Figure 4-19 consists of passive elements. Some of these passive elements suppress the common- or differential-mode noise, and some suppress both.

The differential-mode and common-mode equivalent circuits are shown in Figures 4-20 and 4-21.

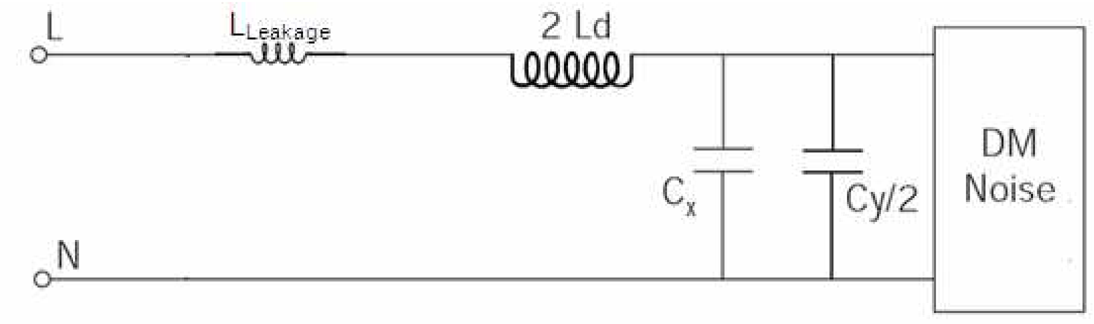


Figure 4-20: DM equivalent circuit

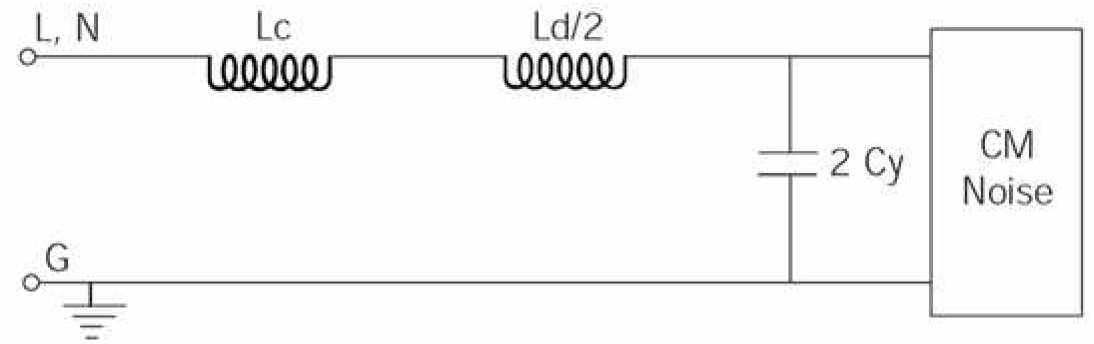


Figure 4-21: CM equivalent circuit

Capacitor C_x is placed to suppress the DM noise. So it is only seen in the DM equivalent circuit. Capacitor C_y is there to suppress both CM and DM noise. So it takes place both in CM and DM equivalent circuit. However C_x is relatively larger than C_y causing the affect of C_y on DM noise to be minimal. L_d suppresses both CM and DM noise too. This time L_c is dominant on suppressing the CM noise because of its relatively large value compared to

L_d. In part 2.9.4.2, it is mentioned that an ideal choke presents zero impedance to the differential mode signal. However in real life, because of the leakage inductance of the choke, it is difficult to observe zero impedance to the differential mode signals. In most cases the inductor L_d is relatively larger than the leakage inductance of the choke.

4.4.3.2 Determining the Filter Components

The cut-off frequency needs to be chosen in order to calculate the required filter components. This frequency can be found graphically by drawing 40 dB/decade slope line tangent to the first peak frequencies of the required CM and DM attenuations shown in Figures 4-17 and 4-18 (See Figures 4-22 and 4-23). 40 dB is the insertion loss of the basic "L" type L-C filter mentioned in part 2.9.

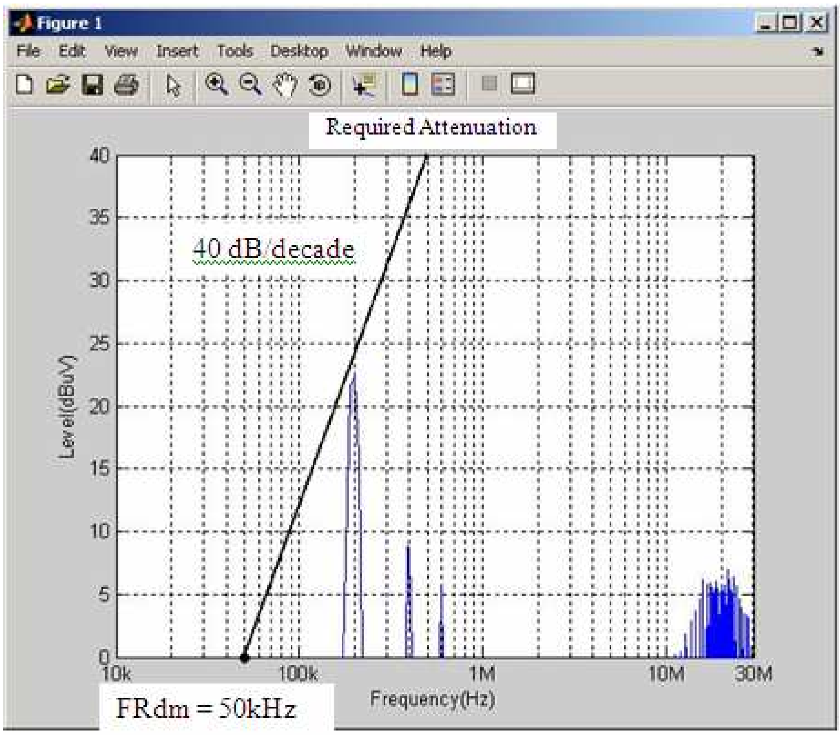


Figure 4-22: Cut-off Frequency for DM noise

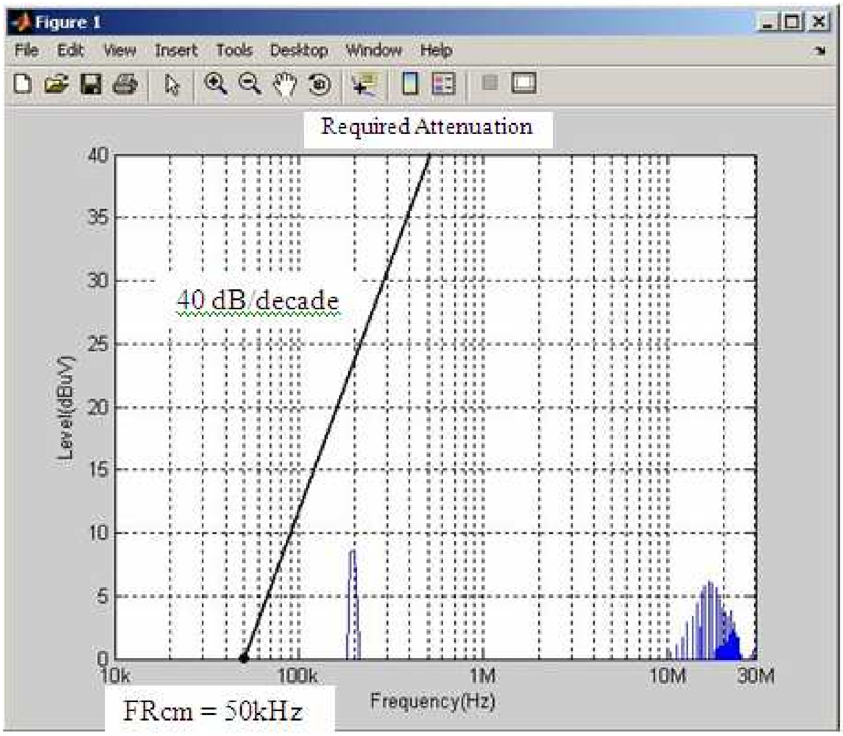


Figure 4-23: Cut-off Frequency for CM noise

From the circuit shown in Figure 4-24, the cut-off frequency(FR_{dm}) of the DM equivalent circuit is found as:

$$FRdm = \frac{1}{2\pi\sqrt{Ldm\ .Cdm}} \text{ where } L_{dm} = 2L_d \text{ and } C_{dm} = C_x$$

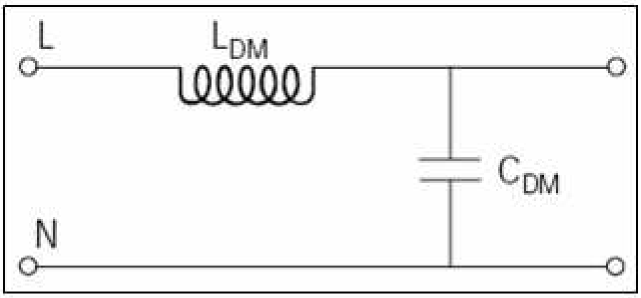


Figure 4-24: CM equivalent

In Figure 4-22, FR_{dm} is choosen 50kHz. So "$L_{dm}.C_{dm}$" product is found as;

$$Ldm\,.\,Cdm = 1{,}013x10^{-11}$$

$C_{dm} = C_x = 1\mu F$ is chosen (See Appendix-A for Cx specifications). From the "$L_{dm}.C_{dm}$" product;

$$L_{dm} = 2L_d \approx 10\ \mu H \Rightarrow L_d \approx 5\mu H$$

The value of L_d is chosen as 4,7 µH (See Appendix-A for L_d specifications). In the same manner, from the circuit shown in Figure 4-25, the cut-off frequency (FR_{cm}) of the CM equivalent circuit is found as:

$$FRcm = \frac{1}{2\pi\sqrt{Lcm\,.Ccm}} \text{ where } L_{cm} = L_c + L_d/2 \text{ and } C_{cm} = 2C_y$$

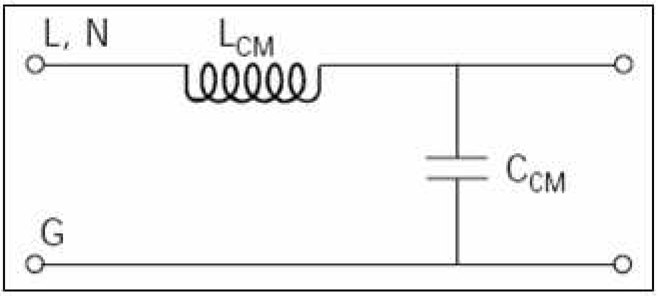


Figure 4-25: DM equivalent

In Figure 4-23, FR_{cm} is choosen 50kHz too. So "$L_{cm}.C_{cm}$" product is same:

$$Lcm\,.\,Ccm = 1{,}013x10^{-11}$$

L_d was chosen before. Now, L_c or C_y has to be chosen to solve the equation. For common-mode choke, 36-00037 part numbered product of

VICOR Corporation is choosen (See Appendix-A for common-mode choke specifications).

For L_c = 330µH, L_d = 4,7 µH ➔ L_{cm} = 332,35 µH. From the "$L_{cm}.C_{cm}$" product;

$C_{cm} = 2C_y \approx 30nF$ ➔ $C_y \approx 15$ nF. The value of C_y is chosen as 15 nF (See Appendix-A for C_y specifications).

It should be noted that this design procedure uses ideal filter components with neglecting parasitic effects. Additional filter components may be needed because of the high frequency parasitic effects. However, these additional high frequency filter components are rather small compared to the other filter components

4.4.3.3 Designed EMI Filter

The circuit shown in Figure 4-26 is drawn on the Mentor Graphics which is a software tool for electronic circuit design and PCB layout.

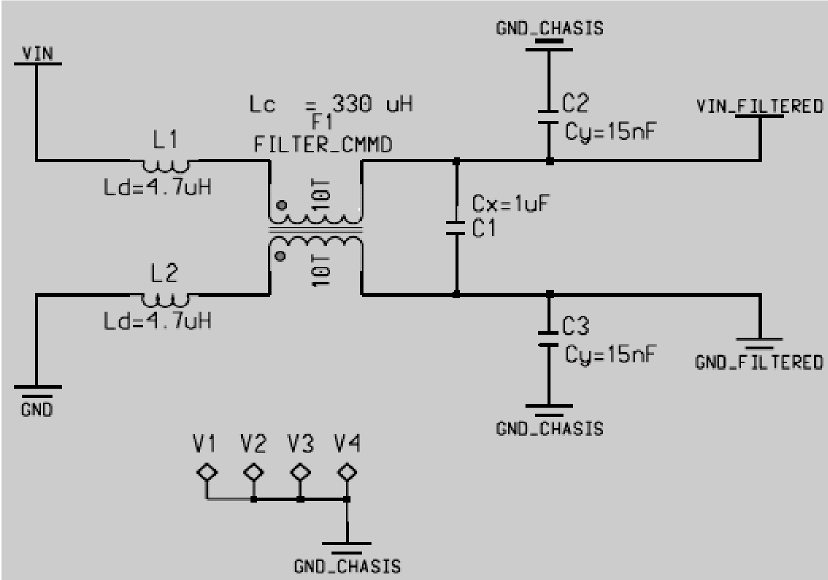


Figure 4-26: Designed Filter circuit

The implemented EMI filter is shown in Figure 4-27. For a good grounding, a wide chassis layer is implemented on the layout. An aluminum plate is conducted to the chassis layer by the four aluminum bosses and screws (See Figure 4-28).

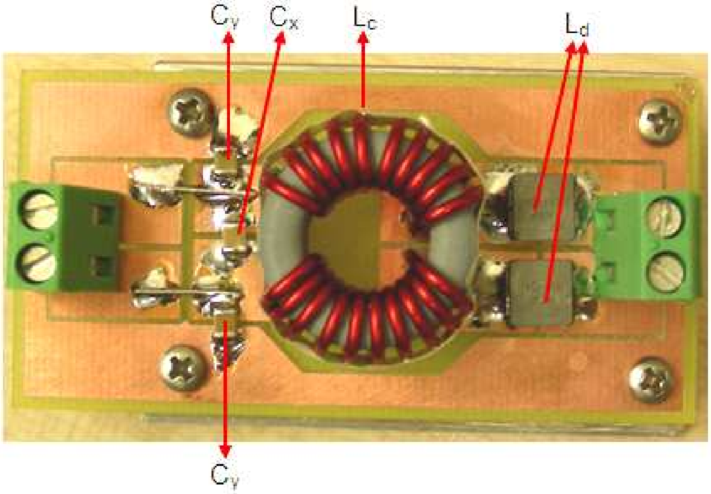


Figure 4-27: Designed Filter

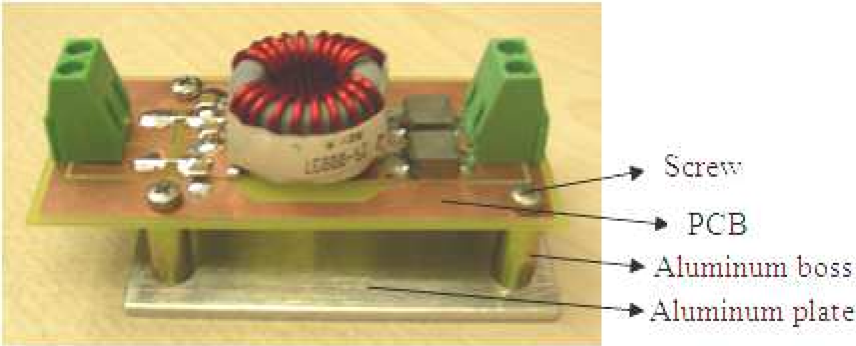


Figure 4-28: Aluminum Plate Connection of The Designed Filter

4.5 Conducted Emission Measurements After Filtering

Test configuration shown in Figure 4-4 is used for CE measurements while the supply input of the EPQM is filtered by the designed filter.

4.5.1 Positive Line Measurement

A CE measurement is taken while the average detector is coupled to the LISN on the positive line. Figure 4-29 shows the conducted noise level on the positive line.

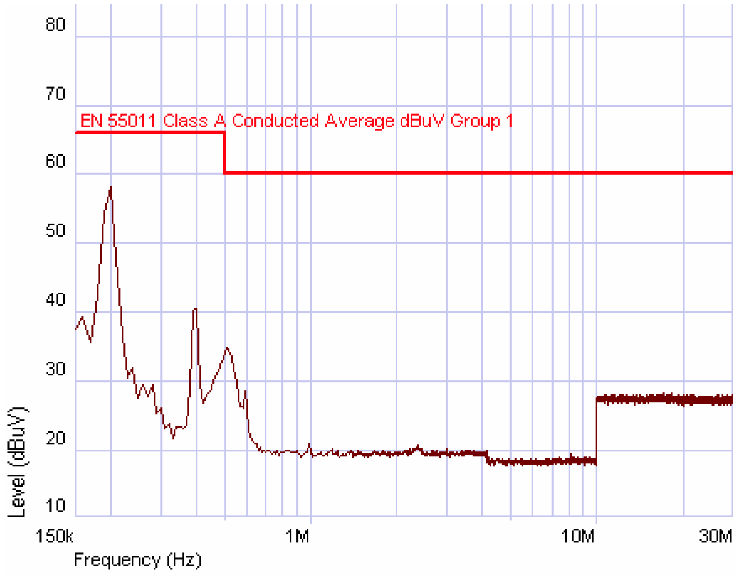


Figure 4-29: EPQM Noise Level on the Positive Line with filter

4.5.2 Negative Line Measurement

A CE measurement is taken while the average detector is coupled to the LISN on the negative line. Figure 4-30 shows the conducted noise level on the negative line for this configuration.

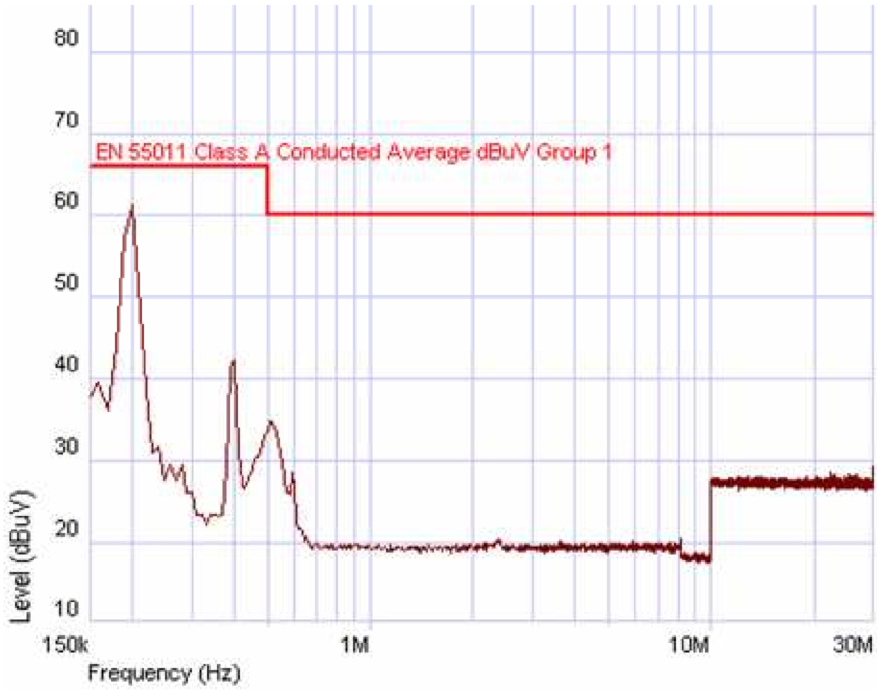


Figure 4-30: EPQM Noise Level on the Negative Line with filter

4.5.3 Results and Discussions for Conducted Emission Tests

Resultant conducted emission noise levels of EPQM shown in Figures 4-29 and 4-30 are below the limits. Thus, conducted emission part of CISPR11 is satisfied by using a filter on the power line of EPQM.

Although the noise peaks at 200 kHz and at its harmonics are attenuated well, there is still a peak at 200 kHz. As this peak is under the conducted emission limit line given for CISPR11, it is not a problem anymore.

At higher frequencies the noise levels are remained below the limit line too. Between 700 kHz and 10 MHz noise levels seem to stay constant at 20 dBµV. This value is the resolution level of the spectrum analyser set in the test procedure. So for this frequency range, noise levels are below 20 dBµV. Same situation is valid for the frequency range of 10 MHz–30 MHz. However this time, noise levels seem to stay at around 30 dBµV. This is because different resolution levels are used for different frequency ranges in the test procedure. So noise levels are below 30 dBµV for the frequency range of 10 MHz–30 MHz. The noise problem for higher frequencies is also solved by the designed filter.

4.6 Radiated Emission Test According to CISPR 11

4.6.1 Test Setup

Typical CISPR 11 radiated emission test setup is shown in Figure 4-31. In this test configuration, radiated signal levels have to be measured for both horizontal and vertical polarization of the measurement antenna while EUT is placed on a table 80cm above the ground.

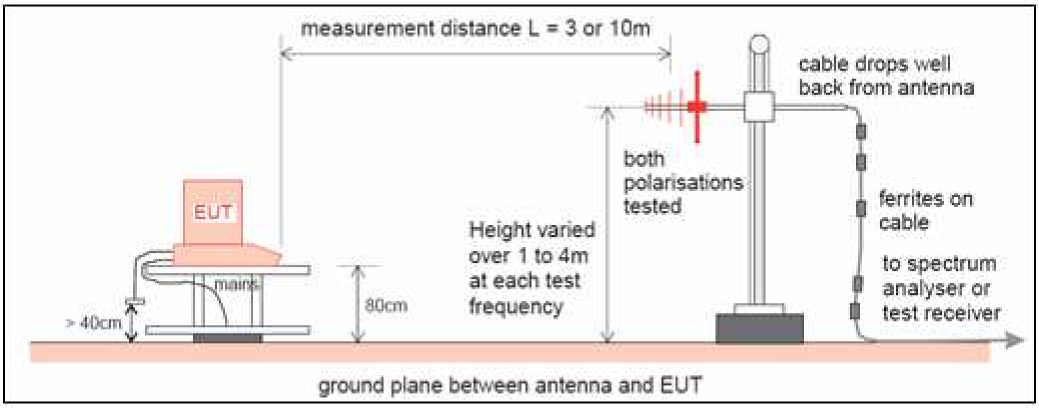


Figure 4-31: CISPR 11 RE Test Setup

It is possible to simulate this polarization of the measurement antenna by doing the measurement with a GTEM cell (See Figure 4-32). In the radiation tests done by using the typical setup, the antenna type has to be changed for different frequency ranges. However with GTEM cell, size and scaling problems are solved. So testing can be done without antenna changes associated by the typical setup.

Figure 4-32: GTEM Test Cell of Schaffner

The GTEM cell is a frequency extended variant of the traditional TEM (Transverse Electro-Magnetic) cell. The GTEM cell is, in principle, a tapered coaxial line (offset septum plate), from a coaxial feeding point, having an air dielectric and a characteristic impedance of Z = 50 Ω [40].

This coaxial line is terminated by a combination of discrete resistors and RF absorbers to achieve a broadband match. The outer conductor of this “coax line” is created by the metal walls of the cell which provide screening for both internal and external electromagnetic fields [40].

The introduction of a device that radiates a field in the volume under the septum will produce an RF voltage at the GTEM input connector. The voltage produced will be proportional to the intensity of the radiated field [41].

At the feed-point of the GTEM cell, it is possible to measure EUT emissions. This is achieved by placing the EUT in three orthogonal planes. The results are then converted by means of a ‘GTEM correlation’ into a field intensity value. The correlation equations for remote field calculations (applicable when GTEMs are used in the >30 MHz frequency range) are formed by the computation of a multipole model of a configuration of three orthogonal axes [40].

4.6.2 Measurements

Radiated emission tests are done in GTEM Cell. In part 4.2.4, test levels for measurements at test area are given for 10m. So GTEM cell is simulated for 10m before the measurements (See Figure 4-33). The GTEM correlation factors are found by the help of the Schaffner Compliance 3 software, and used for the emission test.

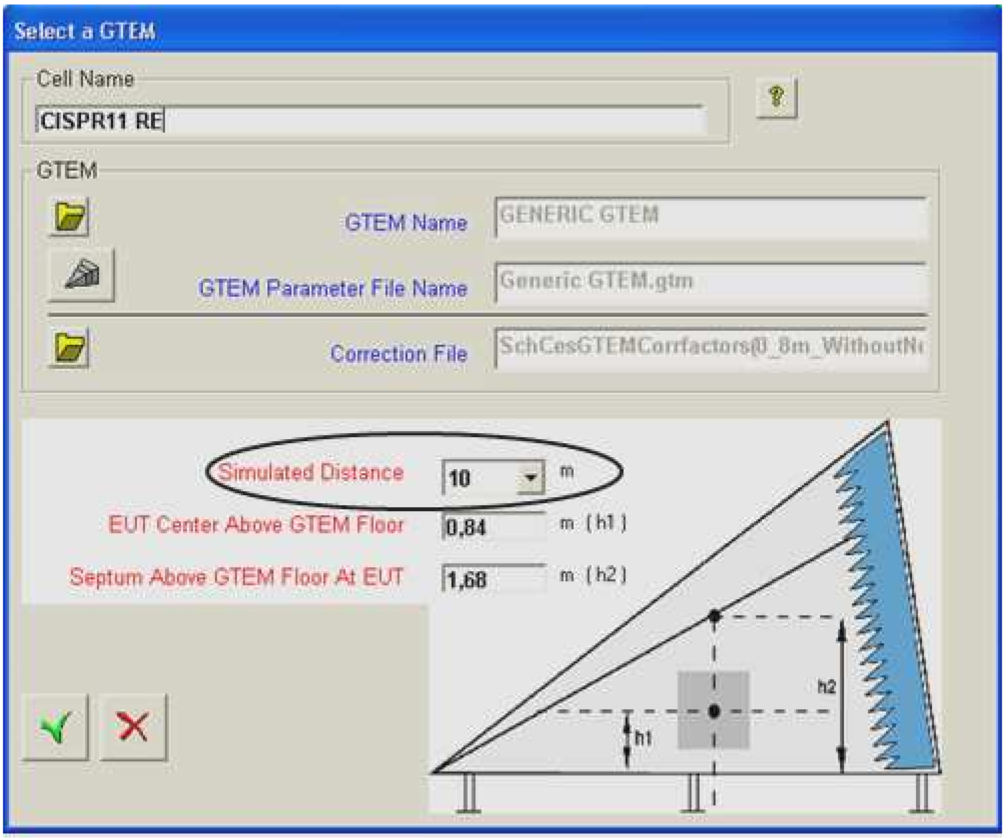


Figure 4-33: 10m simulation in GTEM Test Cell

4.6.2.1 Measurements without Any Countermeasures

EPQM is placed on the XYZ manipulator in GTEM cell (See Figure 4-34).

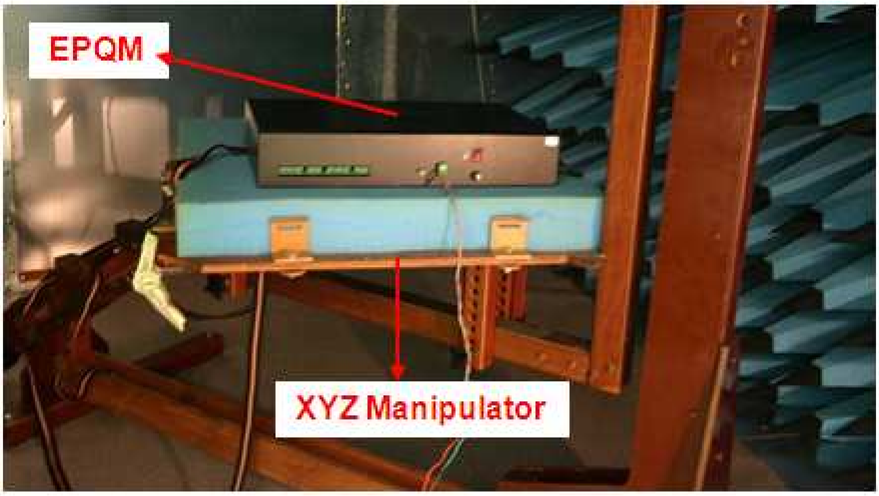


Figure 4-34: EPQM in GTEM Test Cell

Under ideal circumstances, the magnitude of the field changes gradually from a maximum at the septum, to zero at the outer cell wall (conductor). The uniform area, therefore, lies in the region where this transition in field is within the limits of the specified measurement uncertainty [41].

So in order to observe whether the presence of EPQM affects this uniform area by changing the impedance of the incident field, ambient noise is measured in GTEM Cell while EPQM is not operating. The measured area is given in Figure 4-35.

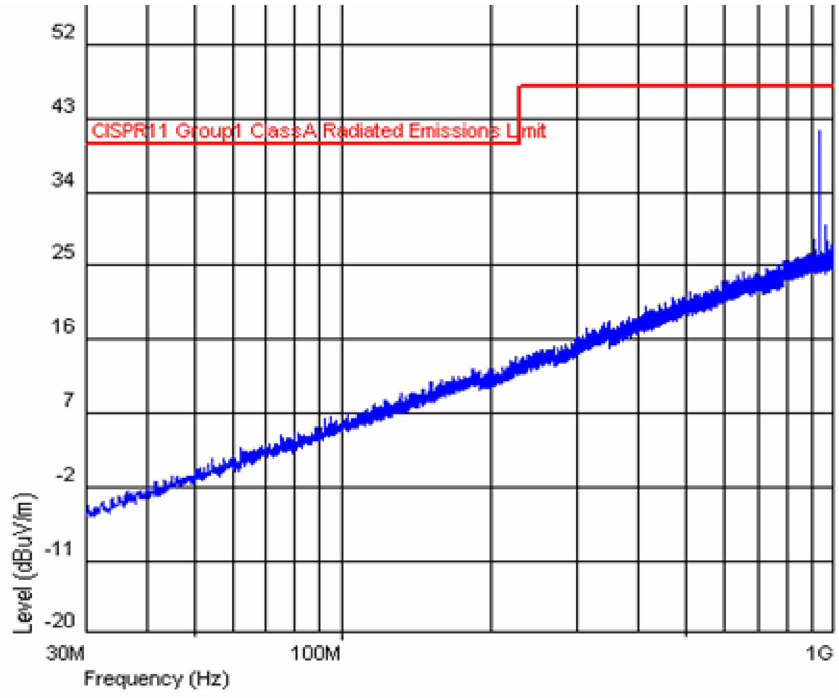


Figure 4-35: Ambient Noise in GTEM Test Cell (Uniform Area)

As the uniform area stays more than 6dB below the limit levels, it is adequate to take measurements. The EPQM is powered on and the embedded measurement program is run. The radiation level measured for EPQM is shown in Figure 4-36.

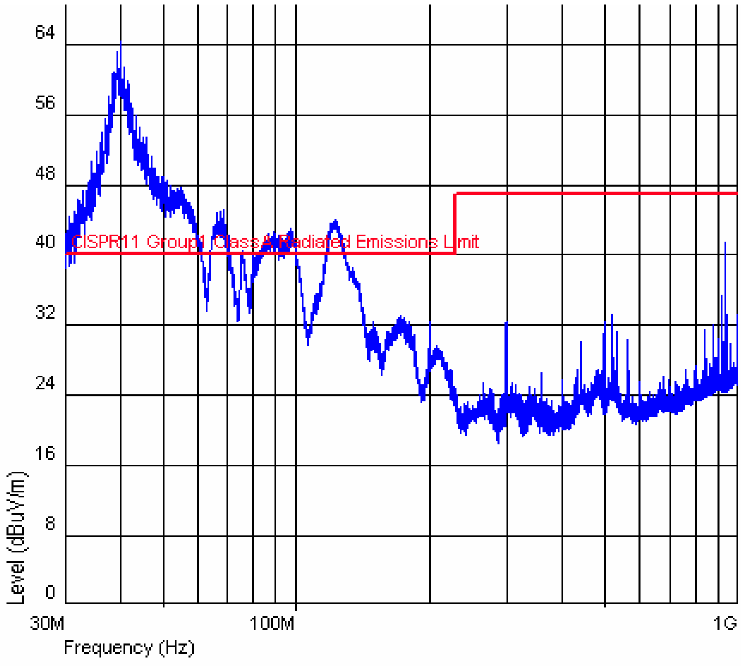


Figure 4-36: EPQM Radiation Level

4.6.2.2 Measurements with Designed EMI Filter

Measurements are taken with two different configurations. First the chassis ground is not tied to the chassis of the box (See Figure 4-37). The results for this configuration are shown in Figure 4-38.

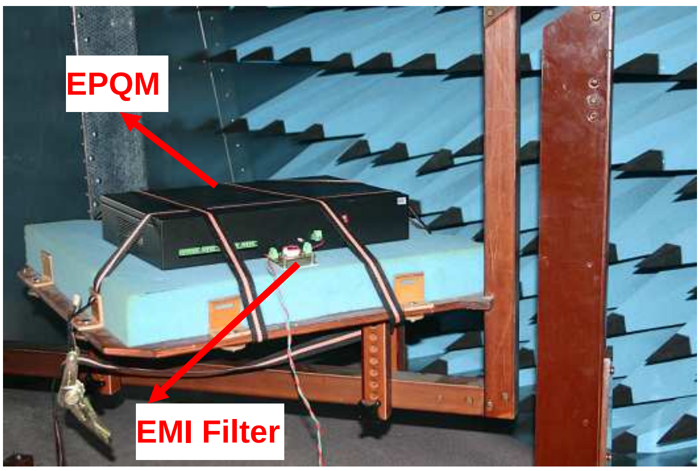


Figure 4-37: RE Test Configuration of EPQM with EMI filter

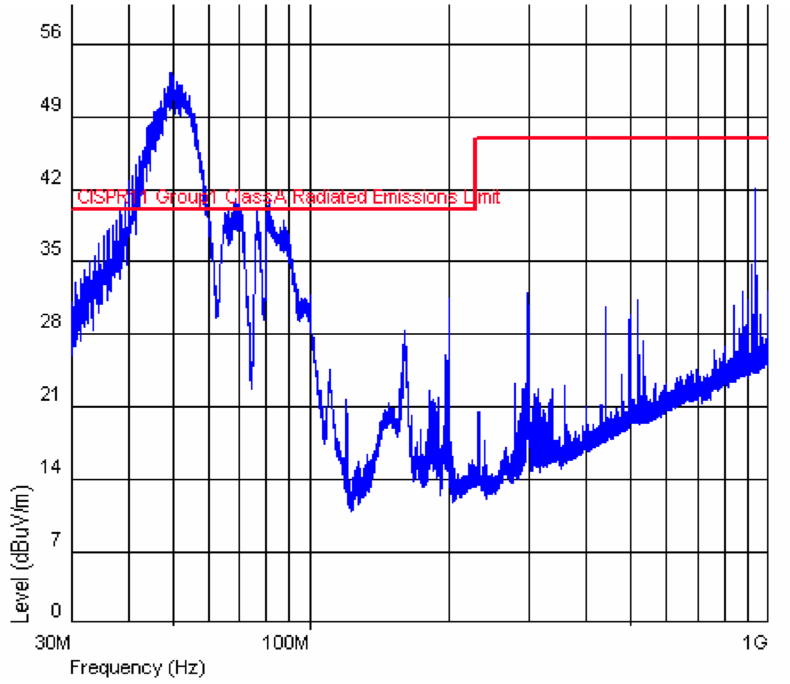


Figure 4-38: Radiation Level with EMI filter – No Chassis Connection

To see the effects of the wide chassis, the chassis ground is tied to the chassis of the box (See Figure 4-39) and measurements are repeated. The radiation levels are shown in Figure 4-40.

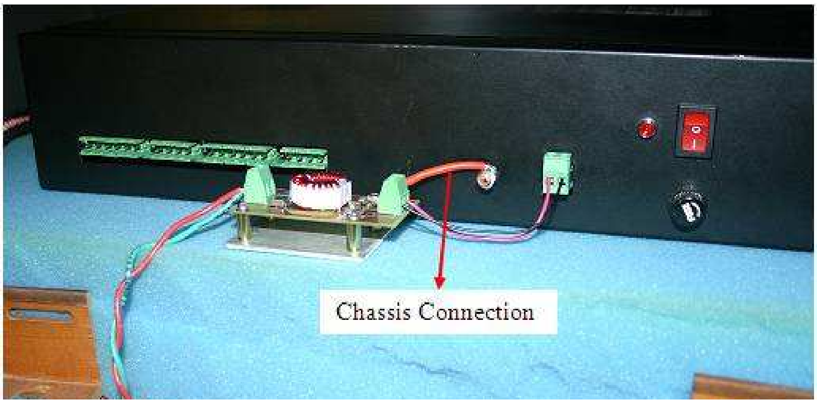


Figure 4-39: Chassis Connection of EMI filter with EPQM box

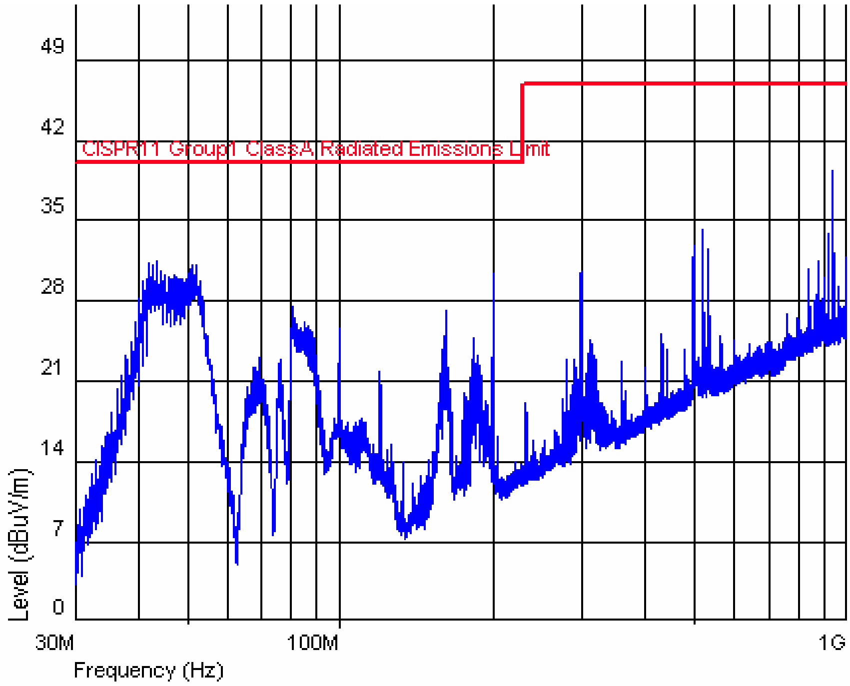


Figure 4-40: Radiation Level with EMI filter – Chassis Connection

4.6.3 Results and Discussions for Radiated Emission Tests

Conducted emissions are currents passing through the power cable of the device. These currents usually radiate from the cables of a system and may contribute to radiated emissions above 30 MHz. Figure 4-41 shows the illustration of the relative radiated electric field caused by the CM and DM currents. So, the radiated emission of a device can give idea about the terminal disturbance caused by the device. The levels measured for 30 -150 MHz frequency range in Figure 4-36 possibly have arisen because of the conducted emission of the device. So normally if a precaution is taken for conducted emission, radiated emission will be affected.

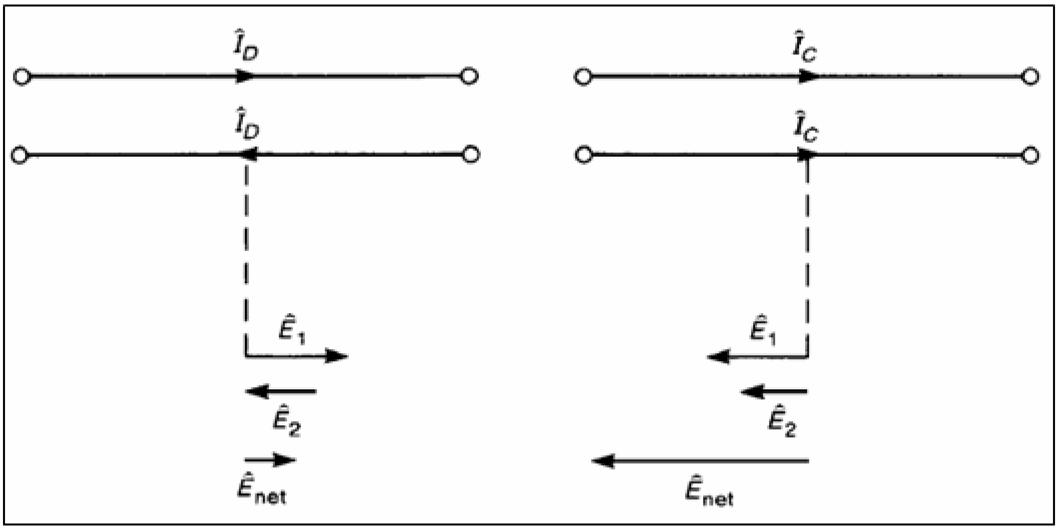


Figure 4-41: CM and DM Currents Producing Radiated Electric Fields

The radiation levels seen at higher frequencies are usually because of the improper casing of the device. For example, the upper cover is electrically isolated from the other parts of the device because of the non-conducting coating. It contacts from only the tie screws which tie the upper cover to the case. So continuity is broken on the upper cover. Thus this cover possibly acts like an antenna for the radiated noise between the cover and the PCBs. Usually ensuring the contact of different pieces of a box fixes this problem. In this way, the box acts like a Faraday's cage against the radiated fields, of course not perfectly, but helps to suppress the noise level radiated out of the box.

However the radiation levels above 150 MHz are already below the limit. So suppressing the terminal disturbance levels will be helpful for the device to pass the radiated emission test. One way to fix this small frequency radiation problem is to shield the cables. However, it is known that shielding will require to be ended on the chassis of the box, in order not to break the continuity. So shielding will not be enough for EPQM cables and also the connectors must have a metallic case in contact with the box case and cable shield. Only this continuity; between the connectors, the cable shield and the box case, can prevent the noise radiation perfectly from the cables. Another way to fix this problem is EMI filtering. Sometimes it is easier to get rid of the conducted noise in order to deal with its radiation affects. As you suppress the conducted noise well, you will have fewer problems with the radiation. So radiated emission measurements are repeated using the filter designed in part 4.4.

Considering the results with EMI filter, without a chassis connection the common mode suppression become difficult due to the fact that a wide chassis is needed for proper CM suppression. Remembering the CM equivalent of the filter circuit given in part 4.4.3.1, with a poor chassis ground, the effect of C_y capacitors on CM noise will decrease significantly as we compare the results in Figures 4-38 and 4-40.

With the chassis connection CM noise is suppressed well and radiation caused by the EPQM is remained under the limits.

CHAPTER 5

EMC IMMUNITY TESTS AND COUNTERMEASURES

5.1 Introduction

Immunity test requirements for the equipment for use in industrial environments defined in EN 61326 are given in Table 5.1.

EPQM is fed through a DC source and does not have I/O signal/control lines directly coupled to its supply. And the I/O signal lines are thought to be kept not longer than 3 meters in proper operation. Concerning these specifications of EPQM, five tests should be applied to the EPQM according to Table 5.1.

IEC 61000-4-2 tests how the equipment is affected by ESD. “Performance criterion A” mentioned in part 2.10.3.2 is usually looked for an equipment when it is subjected to ESD. So EUT shall continue to operate as intended.

IEC 61000-4-3 is for measuring the influence level of the EUT under electromagnetic field usually caused by devices nearby. Performance criterion “A” or “B” is usually acceptable for this susceptability test. Sometimes performance level is specified by the manufacturer, and some degradation in performance is accepted.

IEC 61000-4-4 test is to figure out how the fast transients effect the device. These fast transients act as high ferquency signals and can fool the digital circuits. Usually performance criterion “A” is suitable for a device.

Because it is possible for a device to be influenced by fast transients frequently because of the devices connected to the same power mains.

IEC 61000-4-5 is the surge immunity usually caused by lightning events. To determine the performance criterion for this test, an answer should be given for how critical the operation of the device is.

IEC 61000-4-6 simulates the conducted RF currents and voltages on the cables caused by the RF fields between 150kHz- 80MHz. As in the radiated RF test, performance criterion "A" or "B" is usually acceptable in conducted RF test.

Table 5.1: Immunity Requirements in Industrial Environments

Test Point	Test definition	Standards	Test levels
Cover	Electrostatic discharge (ESD) Electromagnetic field Power frequency magnetic field	IEC 61000-4-2 IEC 61000-4-3 IEC 61000-4-8	4kV/8kV contact/air 10 V/m 3 V/m(e)
a.c power	Voltage dips/short interruptions Electrical fast transient/burst Surge Conducted RF	IEC 61000-4-11 IEC 61000-4-4 IEC 61000-4-5 IEC 61000-4-6	0.5 rev/% 100 2 kV 1 kV(a) / 2 kV(b) 3 V(f)
d.c power	Electrical fast transient/burst Surge Conducted RF	IEC 61000-4-4 IEC 61000-4-5 IEC 61000-4-6	2 kV 1 kV(a) / 2 kV(b) 3 V(f)
I/O signal/ control	Electrical fast transient/burst Surge Conducted RF	IEC 61000-4-4 IEC 61000-4-5 IEC 61000-4-6	1 kV (d) 1 kV(b)(c) 3 V(d)(f)
I/O signal/control directly coupled to supply	Electrical fast transient/burst Surge Conducted RF	IEC 61000-4-4 IEC 61000-4-5 IEC 61000-4-6	2 kV 1 kV(a) / 2 kV(b) 3 V(f)

a) Line to line
b) Line to ground
c) Only for long cables
d) Only for cables longer than 3 meters
e) Only for magnetically immune equipments
f) Applied RF test level is lower than the radiated RF test level. Because applied RF test, generates reflection at any frequency and so it is a difficult test.
g) DC connections between the parts of equipment/system not coupled to DC distribution line are accepted as I/O signal/control lines

Immunity requirements for EPQM are summarized in Figure 5-1.

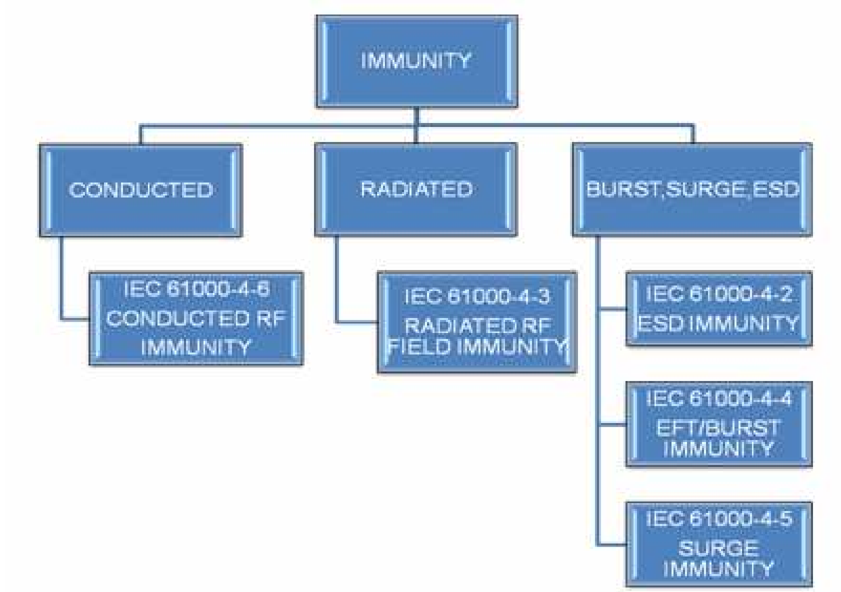


Figure 5-1: EN 61326 Immunity Requirements for EPQM

5.2 ESD Immunity Test According to IEC 61000-4-2

5.2.1 Objective of IEC 61000-4-2

The purpose of this test is to evaluate the performance of the EUT when subjected to electrostatic discharges of ± 4 kV using the direct contact method, and/or ± 8 kV using the through air injection method.

5.2.2 Test Levels

In Table 5.1 test levels for ESD for the equipment for use in industrial environments are given as ±4 kV direct contact and ±8 kV through air injection.

5.2.3 Determining the Test Points

One method may be choosing the weak points such as the edges of the case, the slots, connector openings, display and control panels which may cause ESD pulse to jump another point inside the device. ESD accesed inside of the device can easily damage the electrical circuits.

Another method is to consider the normal usage of the device by the user. Possible points that the user can touch should be tested, however with the exceptions given in part 8.3.1 of IEC 61000-4-2 standard:

- Locations only accesible during maintenance
- Locations only rarely accessed during service by the user (e.g. changing batteries, changing the cassette tape in an answering machine)
- Locations that are not accessible after following the user instructions (e.g. the rear of wall-mounted equipment)
- The contacts of connectors that have a metallic connector shell
- Contacts that are ESD sensitive because of functional reasons and are fitted with an ESD warning label

All these test points mentioned are for direct injection. There is another event that should be simulated by doing injection through air. The device can be influenced by the radiated fields that arise when other devices nearby are subjected to ESD. Performance of the device should be monitored for this condition too.

5.2.4 Test Setup

Typical test setup for IEC 61000-4-2 test is shown in Figure 5-2. A reference ground plane is used during the test. The EUT and its interface cables are isolated from the ground plane by a distance of 0.5 millimeters by an insulation material. ESD gun is grounded to a reference plane and guaranteed to have a good contact. A 0.5m x 0.5m VCP is placed 10 cm apart from the EUT.

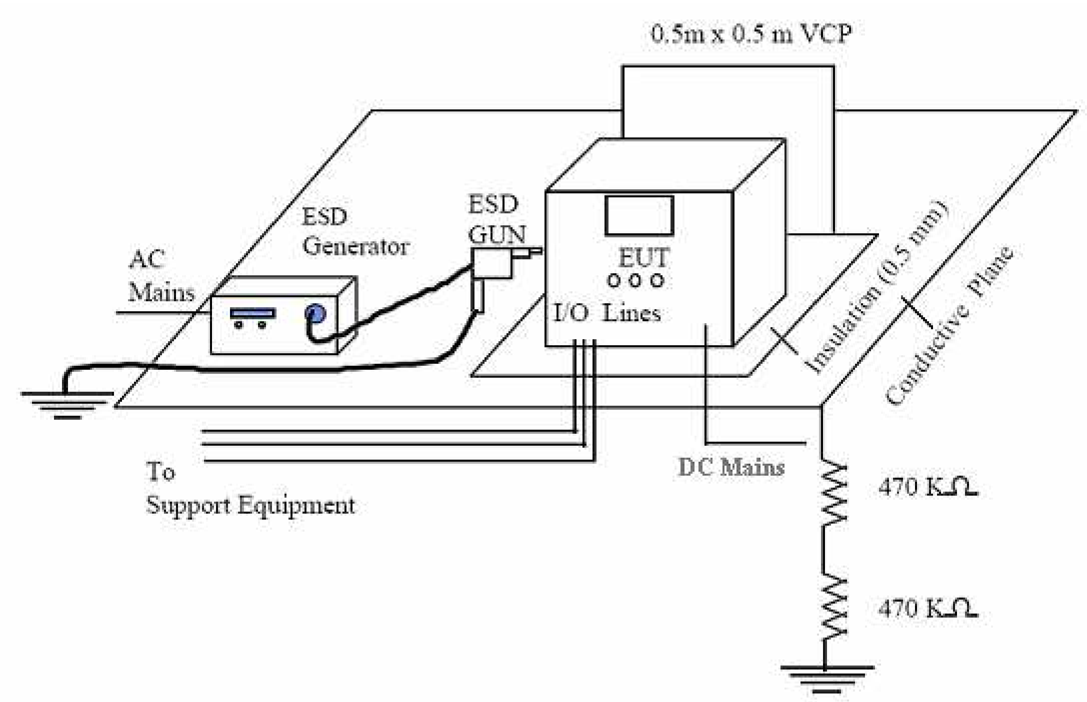


Figure 5-2: IEC 61000-4-2 Test Setup

Test site configuration is done according to this given setup. Ground connection of the ESD generator is shown in Figure 5-3. The DC power supply of EPQM and the PC monitor connected to the EPQM are placed almost 1 meter distant to the test setup as shown in Figure 5-4, so ensuring that they will not be affected by ESD.

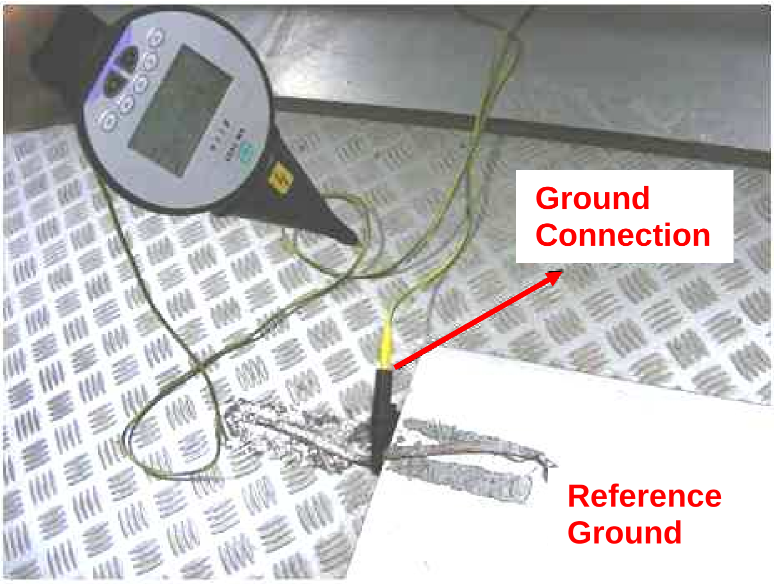


Figure 5-3: ESD generator ground connection

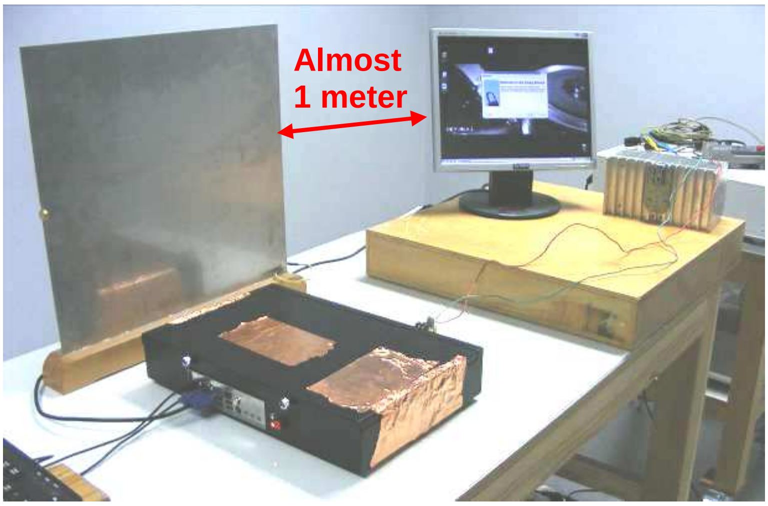


Figure 5-4: IEC 61000-4-2 Test Configuration

5.2.5 ESD Generator

Simplified schematic diagram of the ESD generator is given in Figure 5-5. High voltage pulse is injected through 330Ω using the discharge switch.

Typical current waveform at the output of the generator is shown in Figure 5-6.

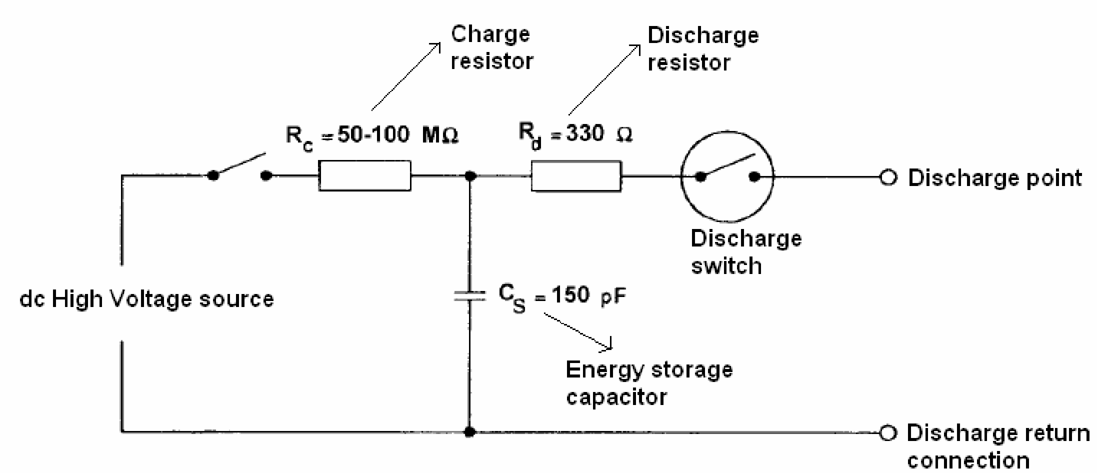


Figure 5-5: Simplified schematic of ESD generator

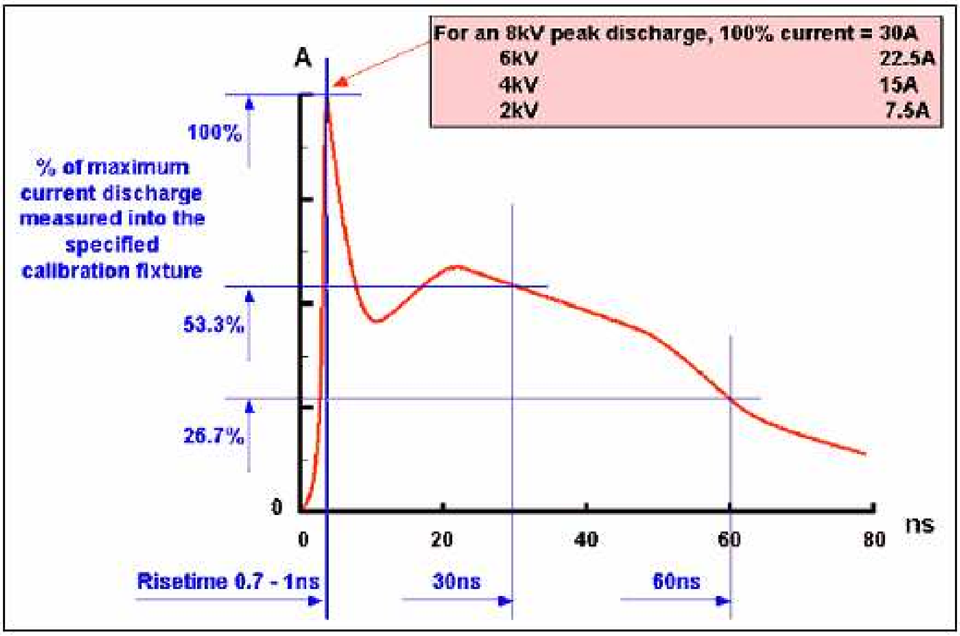


Figure 5-6: Typical waveform of the ESD generator output current

5.2.6 ESD Protections

The slots are covered with a copper material (See Figure 5-7) for two purposes. One is to prevent the direct access of the ESD pulse to inside of the EPQM. The second is to protect the EPQM against the influences caused by the radiation affect of the ESD pulse.

Figure 5-7: ESD countermeasures on EPQM

5.2.7 Measurements and Results

Considering the methods given in part 5.2.3 for determining the test points, some points are chosen on the EPQM. All sides of the EPQM are subjected to ESD. Figure 5-8 shows only one side of the EPQM.

Figure 5-8: One side of EPQM subjected to ESD

Tie screws that connects the top cover of the device with the case are possible points which may cause ESD pulse to jump another point inside the device. So as shown in Figure 5-9, tie screws are subjected to ESD.

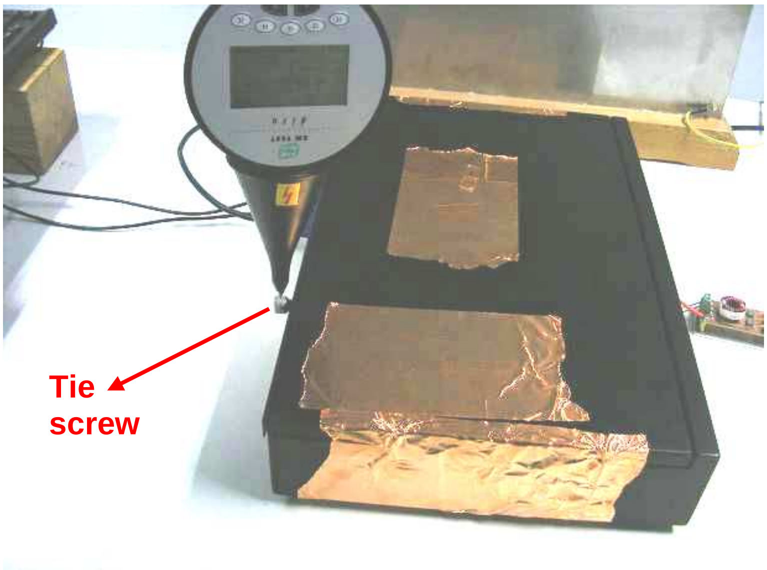


Figure 5-9: Tie screw of top cover is subjected to ESD

Other possible points that can cause a problem are the joints between the top cover and the case (See Figure 5-10). ESD can jump inside from this opening causing damage to the electircal circuits.

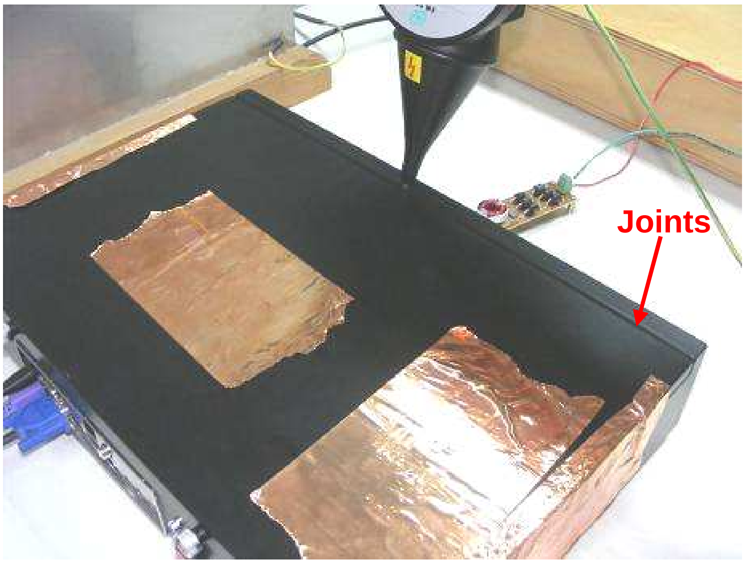


Figure 5-10: Joints of EPQM case subjected to ESD

Another point treated as a weak point is the motherboard panel of the device shown in Figure 5-11. Connections of the peripherals such as PC monitor, keyboard, mouse, USB devices are done from this panel. So it is more probable for the device to face an ESD event from this points.

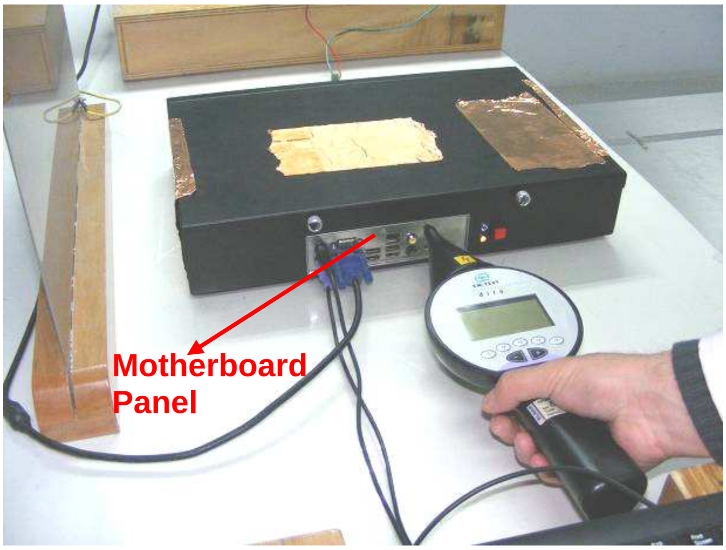


Figure 5-11: Motherboard panel subjected to ESD

All the points until now are subjected to ESD with direct contact. In order to simulate the radiation affect of ESD, ESD pulse is subjected to VCP and the conductive plane placed under the device (See Figures 5-12 and 5-13).

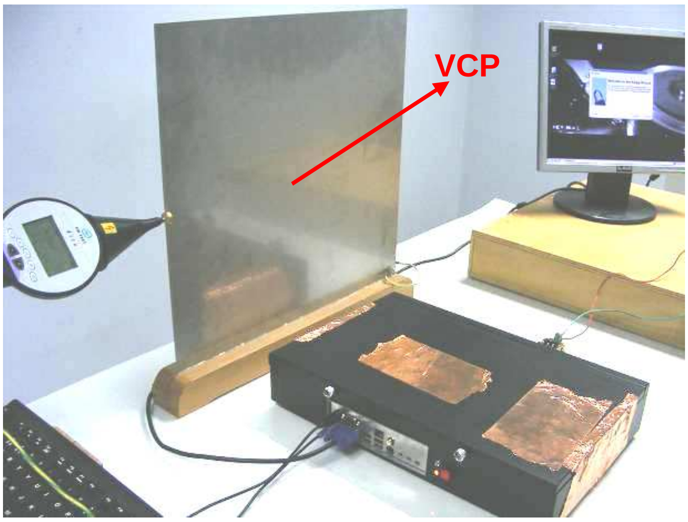


Figure 5-12: VCP subjected to ESD

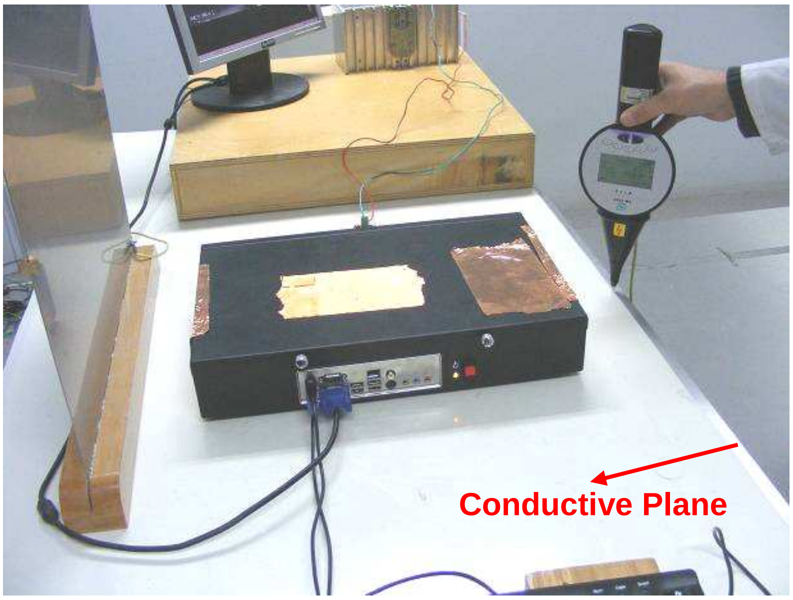


Figure 5-13: Conductive plane subjected to ESD

15V AC voltage supplied from an isolated 220V/15V AC transformer is applied to the voltage measurement input of the device and the measurement program on the EPQM is run during the ESD subjections. The measurement for 15V input is monitored on the screen of the PC monitor. There is no change in reading during and after the test. Also there is no damage on the device. So, *performance criterion "A"* is satisfied by the EPQM when it is subjected to ESD pulses.

5.3 Radiated RF Field Immunity Test According to IEC 61000-4-3

5.3.1 Objective of IEC 61000-4-3

This standard includes the immunity of electrical and electronic equipments against the radiated electromagnetic field. This standard states the levels of experiment and necessary experiment processes. The aim of this standard is to establish a common reference to evaluate the operating quality of electrical and electronic equipments when exposed to radio frequency electromagnetic field.

5.3.2 Test Levels

The test levels in the frequency range of 80 MHz – 1000 MHz are given in Table 5.2.

Table 5.2: IEC 61000-4-3 Test Levels

LEVEL	TEST FIELD LEVEL (V/M)
1	1
2	3
3	10
X	Custom
Note : X is a custom level, changes due to the environment	

Test levels should be chosen considering the electromagnetic radiation environment the device under test would encounter when it is finally installed. The levels in Table 5.2 are described in IEC standard 61000-4-3 as:

- Level 1 : Low level electromagnetic radiation environment. The typical levels of the local radio/television stations and low power receiver/transmitters located at a distance more than 1 km.
- Level 2 : Average level electromagnetic radiation environment. Levels for limited operation very near the low power mobile receiver/transmitters (typically less than 1 W). Typical commercial environment.

- Level 3 : High level electromagnetic radiation environment. Levels for operation very near the mobile receiver/transmitters (2 W or higher) located at a distance not less than 1 m. Levels for operation very near the high power transmitters and Industrial, scientific and medical (ISM) equipments. Typical industrial environment.
- Level X : X is determined according to the characteristics and operating environment of the device under test.

Considering the characteristics and operating environment of the EPQM and examining the level definitions above, level 3 is chosen as the test level. This level is also defined in Table 5.1 for the equipment for use in industrial environments.

The levels in the second column in Table 5.2 are the levels of the unmodulated signal. To obtain the real interference conditions, %80 amplitude modulated 1 kHz sinus signal is used (see Figure 5-14).

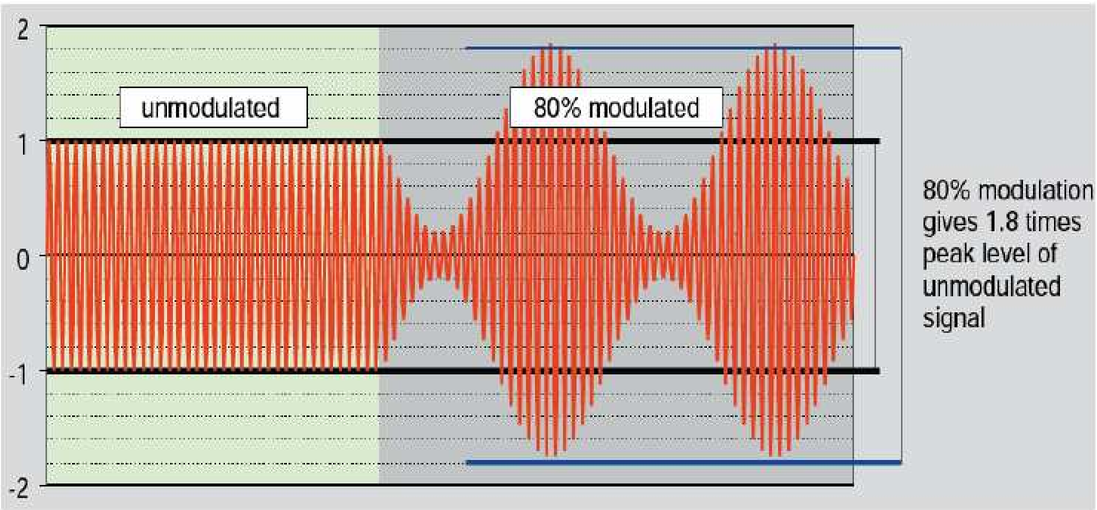


Figure 5-14: Unmodulated and Modulated RF-signal

5.3.3 Calibration

The aim of the site calibration is to ensure the accuracy of experiment results for site regularity on the experiment sample. There must be no modulation during the calibration to be sure that any receiver shows correctly.

The distance between the antenna and the device under test is preferred to be 3 meters. These distances should start from the center of the two conical antenna or the tip of log periodic antenna.

A calibration of the field is preformed to validate the uniform test area (see Figure 5-15). The “uniform area” is a vertical plane in which e-field variations are acceptably small. This uniform area size is 1.5m x 1.5m. An isotropic field strength probe is placed within the empty room connected to the field strength monitor over a fiber optic cable. The signal level to the radiating system is adjusted until the required field intensity is indicated. The frequency range is swept from 80 MHz to 1000 MHz. The voltage or power required at the output terminals of the amplifier to establish the specified field is monitored and recorded. The number of points to be tested to demonstrate uniformity is 16, at 0.5 steps. A field is then verified uniform when its magnitude does not vary over the defined area by greater than -0 dB, + 6 dB of nominal value, over 75% [42].

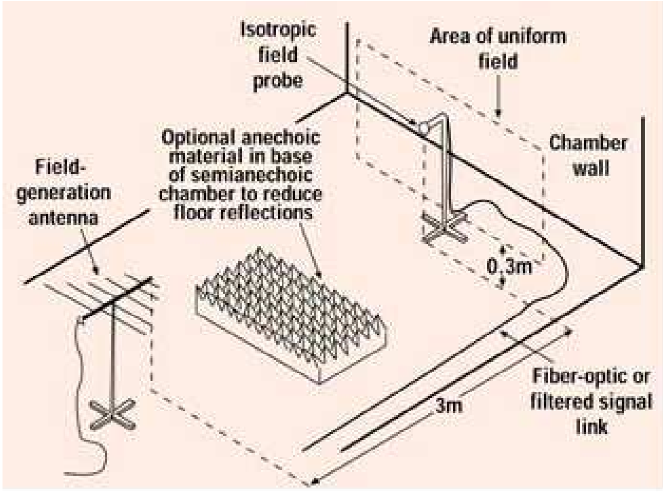


Figure 5-15: Field Calibration Setup

5.3.4 Test Setup

Test is performed in a shielded semi-anechoic chamber (see Figure 5-16). Sweep generator is used to sweep the frequency from 80 MHz to 1000 MHz. Then %80 AM RF-signal is amplified by the amplifier. The field at 10 V/m strength is formed by the transmit antenna.

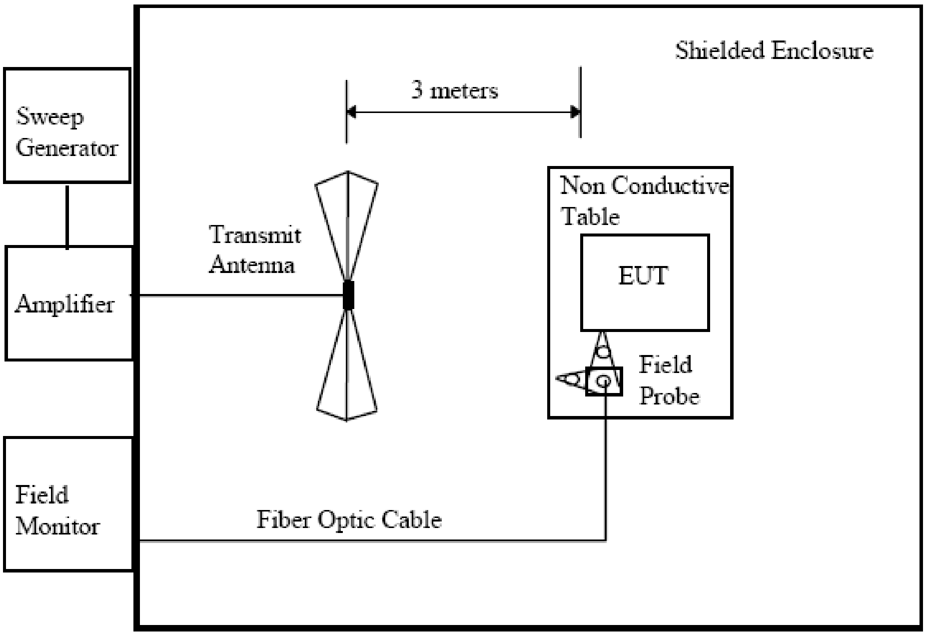


Figure 5-16: IEC 61000-4-3 Test Setup

EPQM is prepared to make measurement by using passive current probes. The position of the measurement system and the distribution of the cables are watched out to be affected mostly by the field intensity taking into consideration the real working conditions (see Figure 5-17).

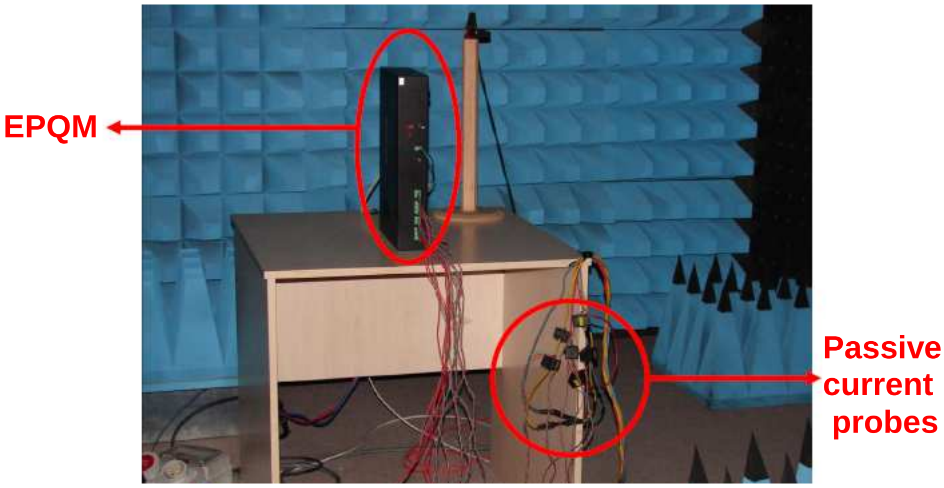


Figure 5-17: IEC 61000-4-3 Test Configuration

5.3.5 Results Under No-field

EPQM is operated under no field condition for a period of time. The measurement results are given in Table 5.3.

Table 5.3: Results Under No-field

Monitor Device(Wh)	Reference Counter(Wh)	Error(%)
25,112	25,09	-0,0877

Before the test, EPQM has been calibrated for measurements with % 0,05 error. It is known that the reference counter gives about % 0,15 error. So it is not clear which device causes the total error. As reference counter is not under field, the measurement results shall be interpreted taking into account the assumption that the error rate between the reference counter and the EPQM will remain stable at the end of the test duration.

5.3.6 Results Under Applied Field

5.3.6.1 Antenna Horizontally Polarized

Field producing antenna is placed horizontally at a distance 3 m to the EPQM (see Figure 5-18).

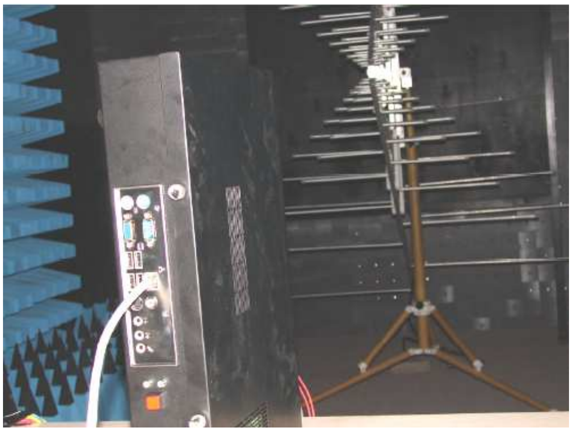


Figure 5-18: Antenna Horizontally Polarized

Performance of the EPQM is monitored while the frequency is swept from 80 MHz to 1000 MHz. The device has continued to operate with no loss of function. In order to check the measurement performance of the device, the measurements are repeated. The measurement results are given in Table 5.4.

Table 5.4: Results under horizontal field

Monitor Device(Wh)	Reference Counter(Wh)	Error(%)
54,754	54,66	-0,17197

If the above results are compared with the results obtained under no field, it is seen that there is a % 0.0842 increase in error. However it can not be understood exactly whether this error rate originates from the field effect or the measurement errors of the equipments.

Ferrite beads are conducted on the cable of the supply input and the cables of the current and voltage inputs (see Figure 5-19).

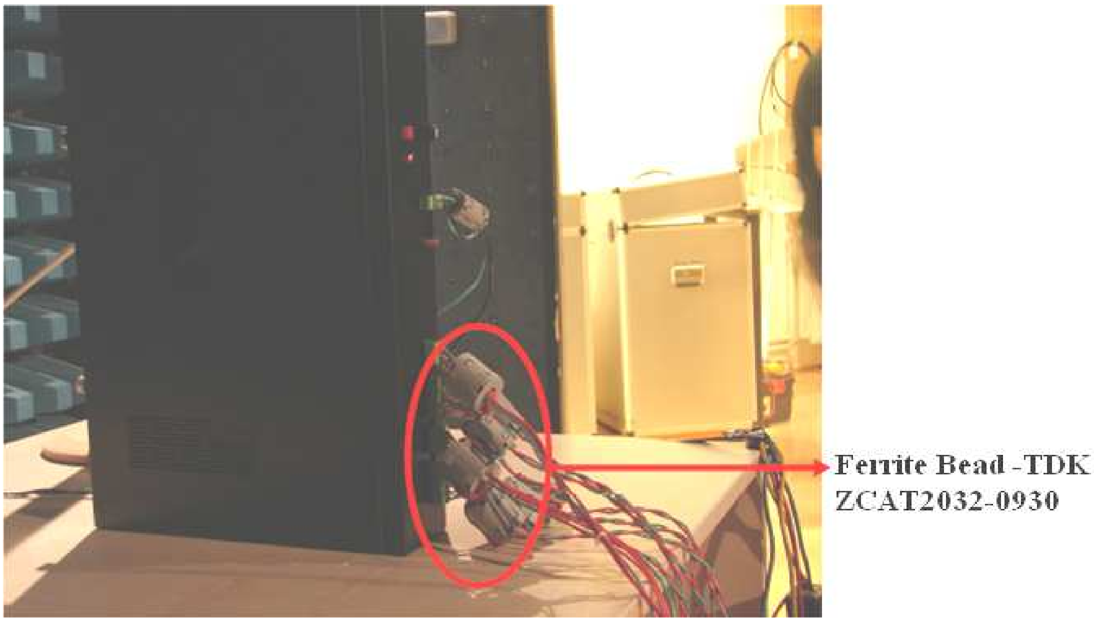


Figure 5-19: Ferrite beads conducted

The test is repeated with the same test conditions. The measurement results are given in Table 5.5.

Table 5.5: Results with ferrite beads conducted

Monitor Device(Wh)	Reference Counter(Wh)	Error(%)
54,805	54,71	-0,17364

Concerning the above results, ferrite beads do not affect the results so much. The error rate is almost same with or without ferrite beads.

Then the position of the EPQM is changed as the slots shown in Figure 5-20 facing the antenna for the maximum penetration of the RF field (see Figure 5-21).

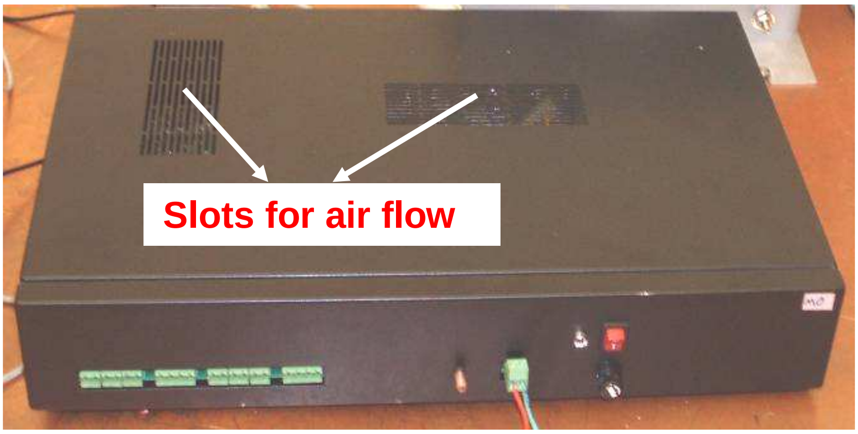


Figure 5-20: Slots on EPQM

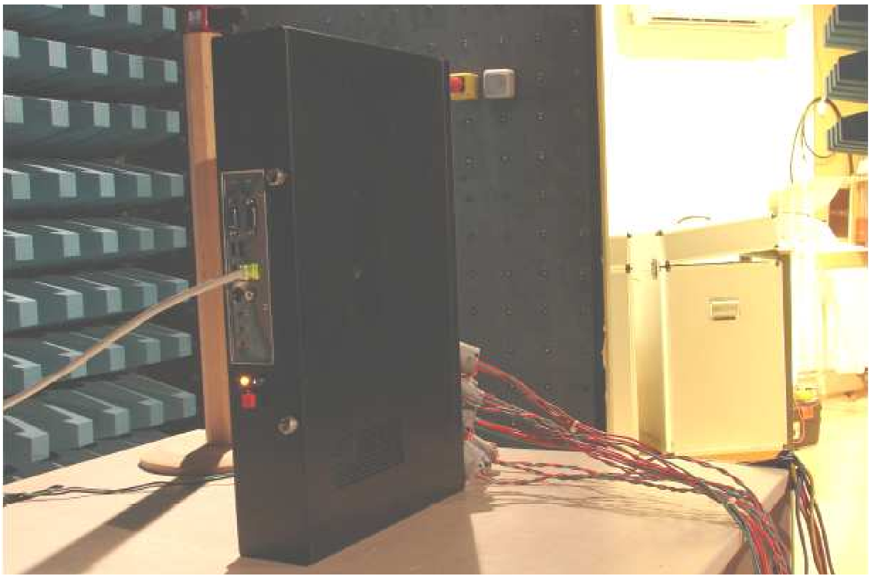


Figure 5-21: Slots facing the horizontally polarized antenna

The test is repeated with the same test conditions. The measurement results are given in Table 5.6.

Table 5.6: Results for the new configuration

Monitor Device(Wh)	Reference Counter(Wh)	Error(%)
54,968	54,87	-0,1786

In this position of the EPQM, no much change in the results is observed.

5.3.6.2 Antenna Vertically Polarized

Field producing antenna is placed vertically at a distance 3 m to the EPQM (see Figure 5-22). The vertical position of both the antenna and the EPQM is evaluated as the worst situation.

Figure 5-22: Antenna Vertically Polarized

Performance of the EPQM is monitored and no loss of function is observed. In order to check again the measurement performance of the device, the measurement is repeated. The measurement results are given in Table 5.7.

Table 5.7: Results under horizontal field

Monitor Device(Wh)	Reference Counter(Wh)	Error(%)
54,864	54,77	-0,17163

Comparing the above results with the results for the horizontally polarized antenna shows that polarization of the antenna does not cause much change on the results for 10 V/m field strength.

Test is repeated with the conducted ferrite beads on the cable of the supply input and the cables of the current and voltage inputs. The measurement results are given in Table 5.8.

Table 5.8: Results with ferrite beads conducted

Monitor Device(Wh)	Reference Counter(Wh)	Error(%)
54,797	54,7	-0,1773

The above results show that ferrite beads do not affect the results so much either as it is for the horizontally polarized antenna.

Then another test is conducted with the configuration that the ventilating openings are facing the antenna for the maximum penetration of the RF field (see Figure 5-23). It is obvious that in this configuration (vertically polarized antenna, vertically located EPQM and slots facing the antenna) EPQM will be affected by the RF signal most.

Figure 5-23: Slots facing the vertically polarized antenna

The measurement results are given in Table 5.9.

Table 5.9: Results for the new configuration

Monitor Device(Wh)	Reference Counter(Wh)	Error(%)
54,427	54,33	-0,1785

Again comparing the above results with the results for horizontal polarization of antenna shows that polarization of the antenna does not cause much change on the results for 10 V/m field strength.

5.3.7 Results for 30 V/m Field Strength

Field producing antenna is placed vertically at a distance 3 m to the EPQM. Both the antenna and the EPQM are placed vertically. The performance of EPQM is monitored while the frequency is swept from 80 MHz to 1000 MHz at 30 V/m field strength. Around 100 MHz, the EPQM goes in system reset. The possible reasons are listed below.

- The power supply unit in EPQM is affected by the field. The output voltage of the DC-DC converter in the power supply unit might have dropped below the minimum operating range of the electrical circuits fed from it.
- Other unit/units in EPQM is/are affected by the field and causes/cause the power supply to shut down because of the current limit.

As a precaution, aluminium foil bonded to the slots and connector sides on the EPQM (see Figure 5-24) and test is conducted again.

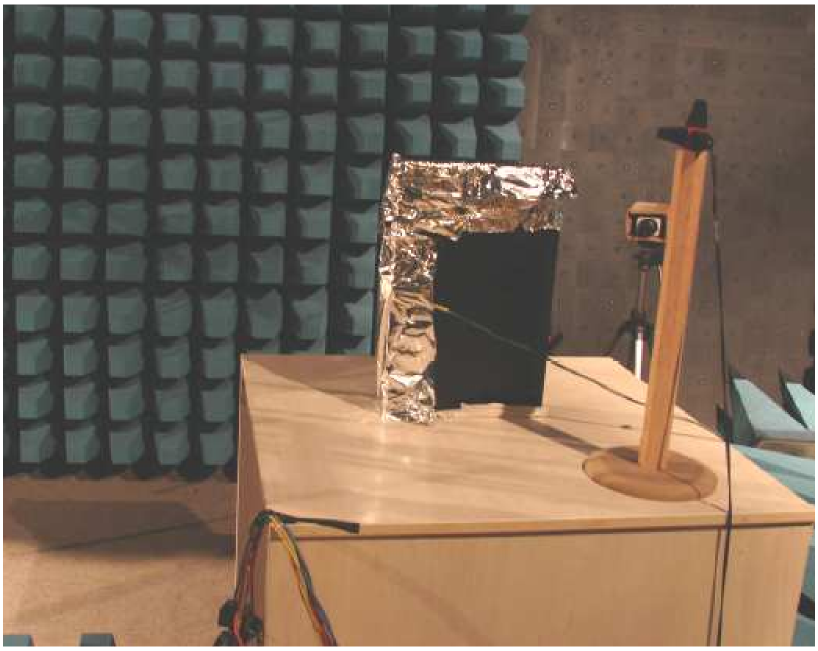


Figure 5-24: Aluminium foil bonded to the EPQM

However, the same problem is observed around 100 MHz.

5.3.8 Results and Discussions

The whole tests show that the measurement error observed under no-field is close to the results under field. Either the position of the EPQM or the polarization of the antenna does not change the error so much. Ferrite beads do not change the error either.

In Table 5.1 test levels for RF electromagnetic field immunity of the equipment for use in industrial environments are given as 10 V/m. Due to the results under 10 V/m field, the largest value of error (% -0,1786) is observed while the slots of EPQM are facing the field producing antenna. This error is two times the error under no field. If EPQM is accepted as a counter device *performance criterion "B"* is satisfied by the EPQM. If EPQM is accepted as a power quality monitor, it is difficult to determine the performance criteria while a standard error is not defined for a power quality monitor device.

Even though level 3 appears to be adequate for the EPQM considering the environment that it will be finally installed, higher field strength of 30 V/m is applied in order to simulate the effects of higher interference sources that may be placed near EPQM. Concerning the observed problem around 100 MHz, the research must be concentrated on the power supply unit. A simple precaution for this problem could be the shielding of the power supply unit with EMI protective cover.

5.4 Countermeasures for EFT/Burst and Surge Tests

In IEC 61000-4-4 EFT/Burst immunity and IEC 61000-4-5 surge immunity standards, different shaped transient pulses are conducted to the EUT using different discharge resistance values. Taking into consideration the pulse shape causing the worst case and using the background given in parts 2.7 and 2.8, a transient protection circuit should be designed to cover both tests.

5.4.1 Approach for Designing a Transient Protection Circuit

5.4.1.1 Pulse Shape Comparison

The common aspect of IEC 61000-4-4, and IEC 61000-4-5 standards is to figure out how the EUT is affected by transients. However in each standard, test conditions try to simulate different situations. IEC 61000-4-4 standard deals with the transients observed when a mechanical switch or a relay is suddenly opened or closed. IEC 61000-4-5 is defined for surges caused by for example lightning event. As the causes of the transients to be simulated in each standard are different, the pulse shapes and test configurations are different too.

The purpose here is to design a circuit placed in front of the power supply input to protect the EPQM against all these defined transients. Comparing the pulse shapes is the basic approach to design a protection circuit. It should be determined which pulse will cause the worst situation.

Rise time for the EFT pulse defined in IEC 61000-4-4 is in the order of nanoseconds (See Figure 5-25). This EFT pulse is injected from 50 Ω impedance.

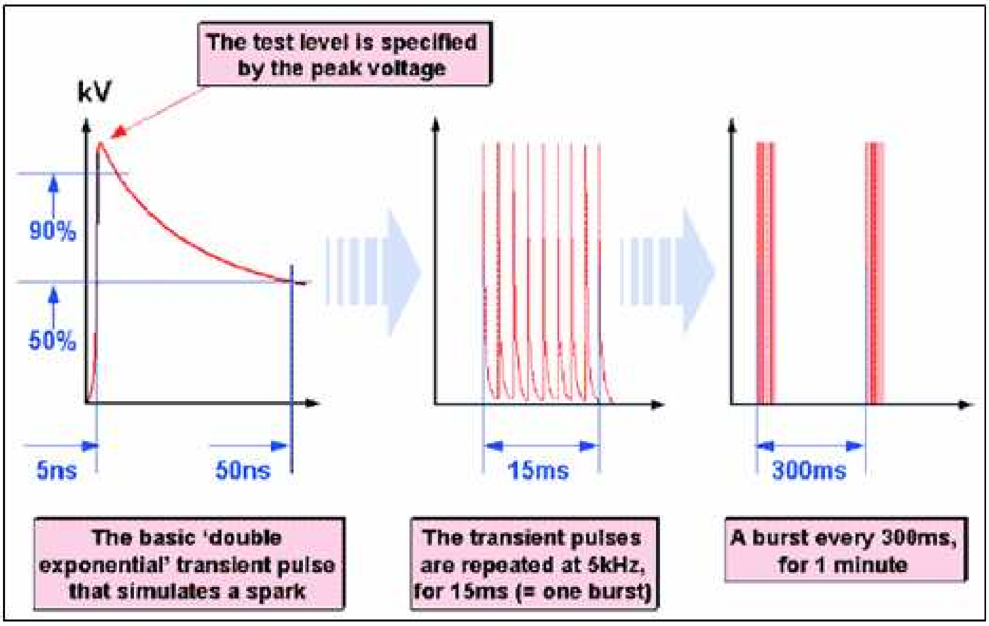


Figure 5-25: IEC 61000-4-4 Fast Transient Burst Waveform

IEC 61000-4-5 simulates surges which is likely to give much more harm to the device. Open circuit voltage waveform defined in the standard is shown in Figure 5-26.

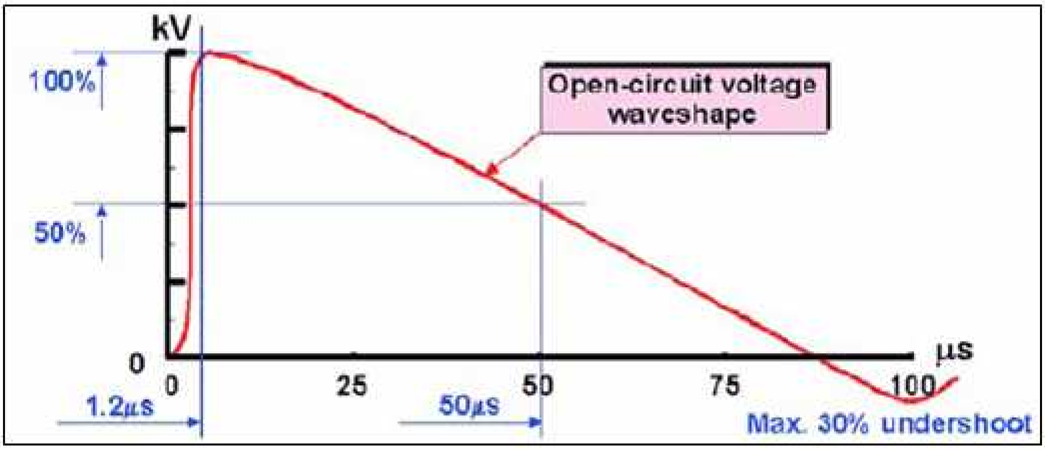


Figure 5-26: IEC 61000-4-5 1.2/50µs Voltage Impulse

Normally the matching impedance for the surge is 2 Ω, but usually a coupling/decoupling network is used that causes a total impedance of 42 Ω which is almost the same with the EFT pulse. The time required for the pulse to drop %50 of its peak value is 50µs. So, rise time for the voltage impulse is in the order of microseconds. This shows that the surge pulse is much wider than the EFT pulse. So the surge pulse is the pulse to be dealt. Surge pulse level will be taken as 4 kV, although maximum 1 kV surge pulse has to be injected according to the standard. So designed transient circuit will fulfill the immunity to pulses with higher energies.

5.4.1.2 Selecting a TVS Device

The operating voltage range of the EPQM is 36-72V DC as mentioned in part 3.2. This voltage range only gives the idea that the maximum voltage on the line has to be 72V DC during the surge. Another point that has to be considered is not to disturb the normal operating of the device. The EPQM is thought to be supplied from an AC/DC converter with a 48V DC output. So it should be guaranteed that our protection device will not go into conduction at 48V DC and clamp the voltage below 72V DC during the surge.

Two tranzorbs are thought to be used in series in order to lower the stress on the TVS devices as the surge applied. 15KP26CA part numbered tranzorbs of “EIC Discrete Semiconductor Manufacturer” have 15,000 Watts of peak power capability and are suitable for using against surges. “C” in the part number refers to “bidirectional”. Bidirectional choice is for not being harmed when the supply is given in reverse polarity by fault. The test waveform for 15KP26CA is shown in Figure 5-27 and peak pulse power change with the pulse time according to this test waveform is given in Figure 5-28.

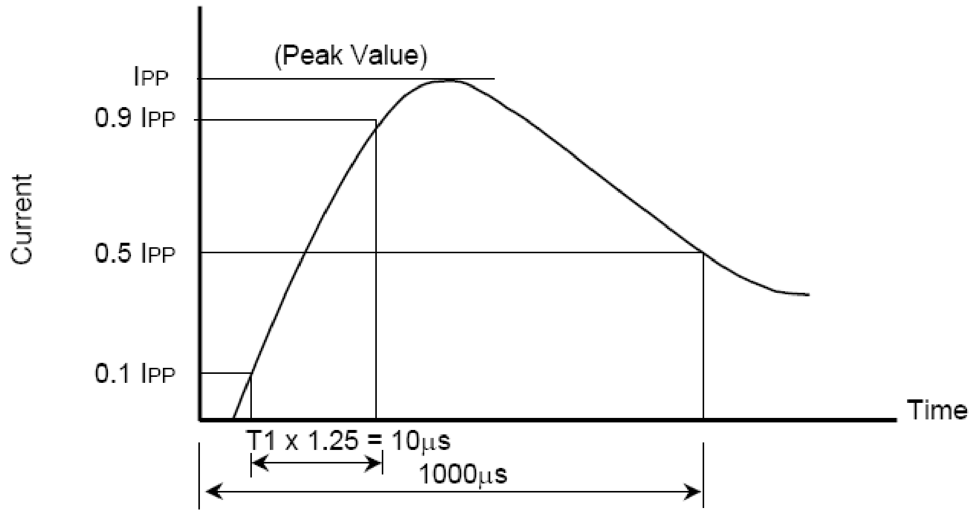


Figure 5-27: Test Waveform for 15KP26CA

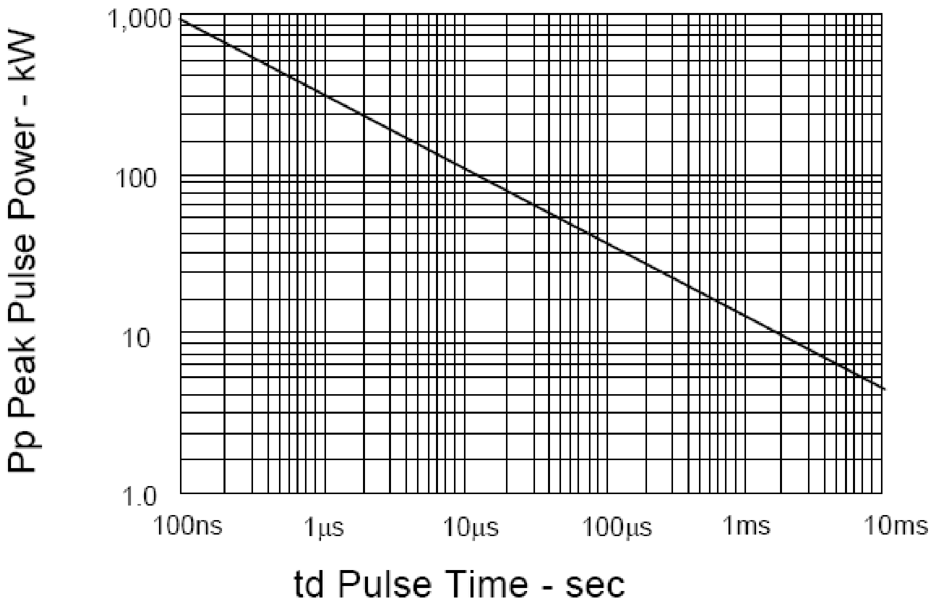


Figure 5-28: Peak Pulse Power vs. Pulse Time

Electrical characteristics of 15KP26CA are shown in Table 5.10. The two tranzorbs in series should not disturb the normal operating, means they should not go into conduction at 48V DC. As V_R (reverse stand off voltage) is 26V DC for one device, the sum of the two devices' V_R will be 52V DC.

Actually V_{BR} (breakdown voltage) is important, because tranzorb starts to conduct at this voltage level. As V_{BR} is 3V above the V_R, there will be no disturbance on the normal operation.

Table 5.10: Electrical Characteristics of 15KP26CA

Part Number (Uni-directional)	Part Number (Bi-directional)	Reverse Stand Off Voltage	Breakdown Voltage @ I_T		Maximum Reverse Leakage @ V_R	Maximum Clamping Voltage @ I_{PP}	Maximum Peak Pulse Current	Max. Voltage Temperature Variation of V_{BR}
		V_R	V_{BR} (V)	I_T	I_R	V_C	I_{PP}	
		(V)	Min.	(mA)	(µA)	(V)	(A)	(mV/°C)
15KP24	15KP24C	24	26.7	5.0	150	45.0	333	30
15KP24A	15KP24CA	24	26.7	5.0	150	40.7	369	27
15KP26	15KP26C	26	28.9	5.0	50	48.7	308	32
15KP26A	15KP26CA	26	28.9	5.0	50	44.0	341	29
15KP28	15KP28C	28	31.1	5.0	25	52.4	286	35
15KP28A	15KP28CA	28	31.1	5.0	25	47.5	316	31
15KP30	15KP30C	30	33.3	5.0	15	56.2	267	37
15KP30A	15KP30CA	30	33.3	5.0	15	50.7	296	33

5.4.1.3 Calculation of TVS Parameters

Peak pulse current rating given in the electrical characteristics of 15KP26CA is for the test pulse of 1000µs shown in Figure 5-27. Considering 1.2/50µs voltage impulse shown in Figure 5-26, the peak pulse current is calculated as:

$$
\begin{aligned}
Ip\ for\ 50\mu s &= (Pp@50\mu s/Ppp@10/1000\mu s)\ x\ Ipp\ of\ 15KP26CA \\
&= (60\ kW/15\ kW)\ x\ 341\ A \\
&= 1364\ A
\end{aligned}
$$

Peak power at 50µs and peak pulse power at 10/1000µs are found graphically as shown in Figure 5-29.

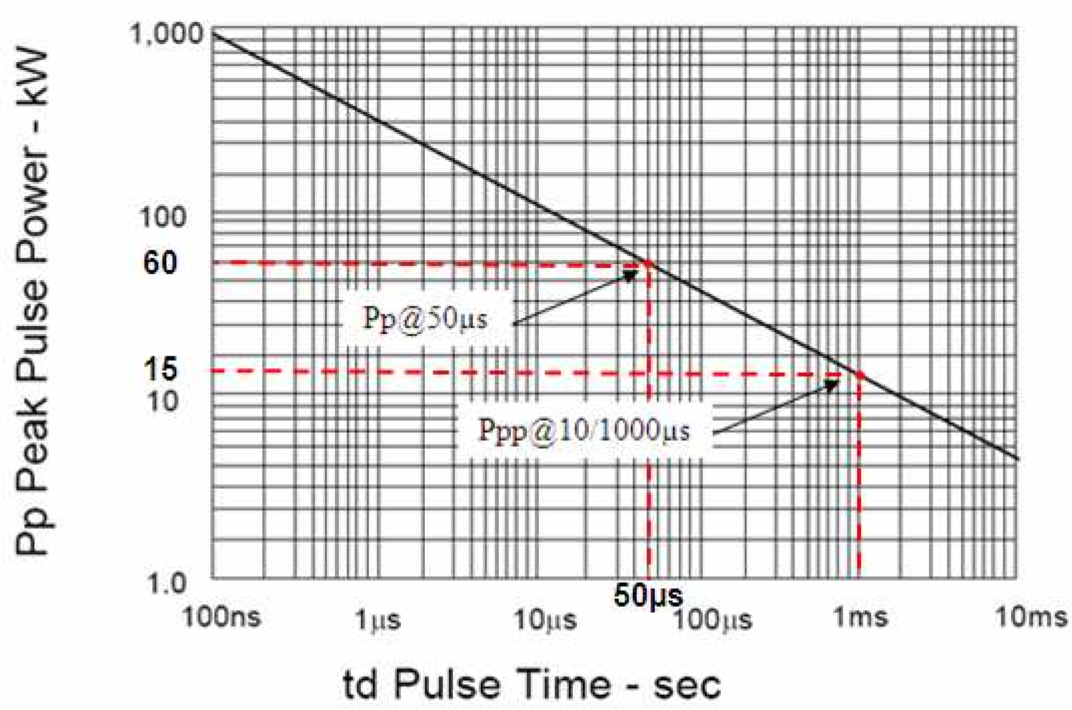


Figure 5-29: Pp@50µs and Ppp@10⁄1000µs

The 1.2/50µs voltage impulse is injected from 42 Ω impedance, as we mentioned earlier. Actual test pulse current (I_P) is the current that passes through the tranzorbs when the pulse is injected (See Figure 5-30).

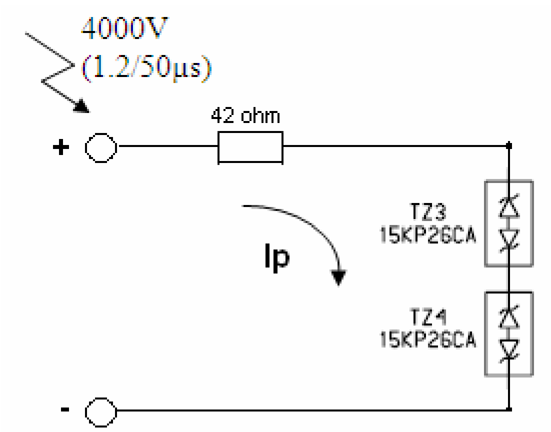


Figure 5-30: Actual test pulse current (I_p)

By taking the maximum clamping voltage (V_C) of each tranzorb as 44V, the short circuit current is calculated as:

$$Ip = \frac{4000-44x2}{42} \cong 93A$$

Now the dissipated power ($P_{dis.}$) on each tranzorb can be found as its voltage and current is known:

$$Pdis. = Vc\ x\ Ip = 44\ x\ 93\ \cong 4.1\ kW$$

This power has to be lower than the power capability of the tranzorb at 50µs. The peak power at 50µs was found as 60kW. However, as the temperature of the tranzorb increases, a reduction in peak pulse power capability occurs. The typical derating curve for a tranzorb is shown in Figure 5-31.

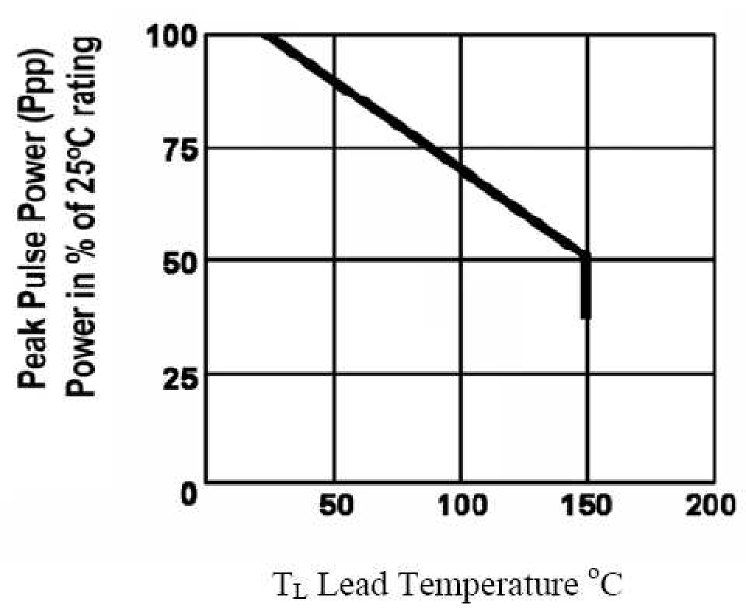


Figure 5-31: Derating Curve

Peak pulse power drops to its %75 of 25^{o}C rating at +80^{o}C. If the derating curve is applied to the peak power at 50µs, it becomes 45kW.

So P_p@50µs > $P_{dis.}$ Is satisfied. However, there's another condition to be satisfied. The sum of the clamping voltage levels of the two tranzorbs (V_{Csum}) under the surge pulse has to be below 72V DC. The clamping voltage can be calculated using the formula:

$$V_C = (I_P/I_{PP})(V_C\ max - V_{BR}\ max) + V_{BR}\ max$$

I_P = actual test pulse current

I_{PP} = maximum rated peak pulse current

V_C = clamping voltage at IP

V_C max = maximum specified clamping voltage

V_{BR} = upper limit of breakdown voltage

Only V_{BR} min is listed on the electrical characteristics of the tranzorb. V_{BR} max can be approximated by multiplying V_{BR} min by 1.20 according to the application note referenced as [43]. So;

I_P = 93 A (previously found)

I_{PP} = 1364 A (previously found)

V_C max = 44 V (given in Figure 5-6)

V_{BR} min = 28.9 V (given in Figure 5-6)

VBR max = 1.20 x VBR min = 34.7 V

Using the values listed above, V_{Csum} is calculated as:

$$Vc = (93/1364)(44 - 34.7) + 34.7 \cong 35.3\ V$$

$$Vcsum = 2\ x\ Vc = 70{,}6\ V$$

So V_{Csum} < 72 V is satisfied too. This value is the maximum value for the total clamping voltage. Exact value might be lower.

5.4.2 Designed Transient Protection Circuit

After selecting the TVS device and calculating its parameters, designed filter in part 4.4 is updated for the transient protection (See Figures 5-32 and 5-33).

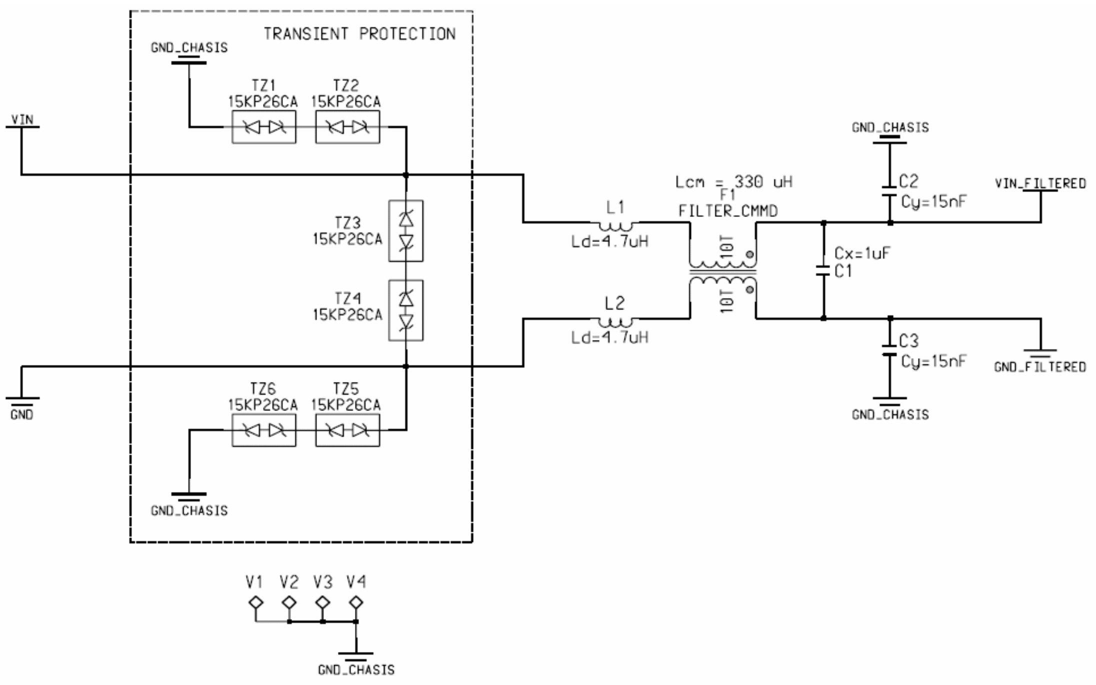


Figure 5-32: Updated Filter Circuit for Transient Protection

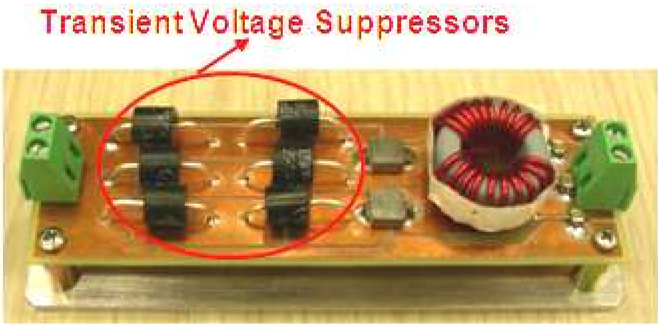


Figure 5-33: Updated Filter Layout

In the new filter layout, the traces between the series tranzorbs and between a tranzorb and the line are kept as short as possible (See Figure 5-34). When a large current passes under a surge pulse, the resistances caused by long traces induces a voltage. This voltage level is added to the clamped voltage level. So the bus voltage is clamped a higher level than its expected value. Keeping the traces short will prevent the unexpected bus voltages under high pulse currents.

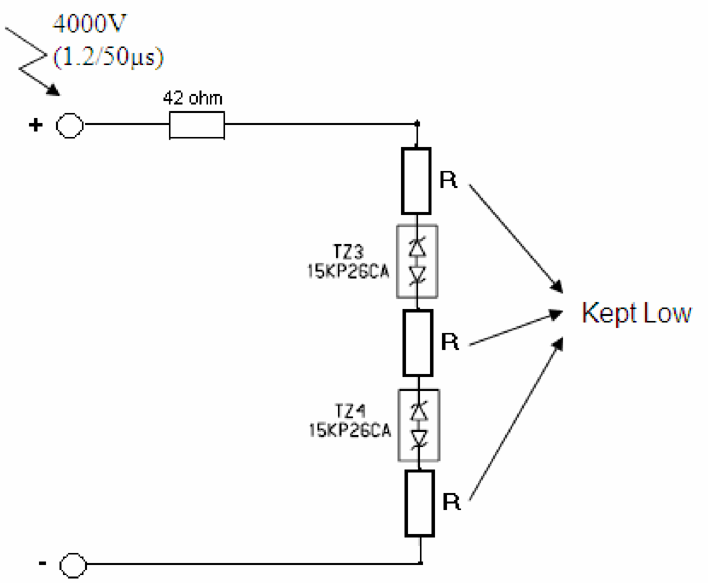


Figure 5-34: Trace Resistances

5.5 EFT/Burst Immunity Test According to IEC 61000-4-4

5.5.1 Objective of IEC 61000-4-4

The purpose of this test is to evaluate the performance of the EUT when subjected to electrical fast transients of ± 2.0 kV on the power lines.

5.5.2 Test Levels

In Table 5.1 test levels for EFT pulses are given as 2 kV. These pulses are injected to both positive and negative lines of the power supply input.

5.5.3 Test Setup

Typical test setup for IEC 61000-4-4 applied to the power lines is shown in Figure 5-35. A reference ground plane is used for the test and EUT is placed on a non-conductive table about 80 cm above this reference plane.

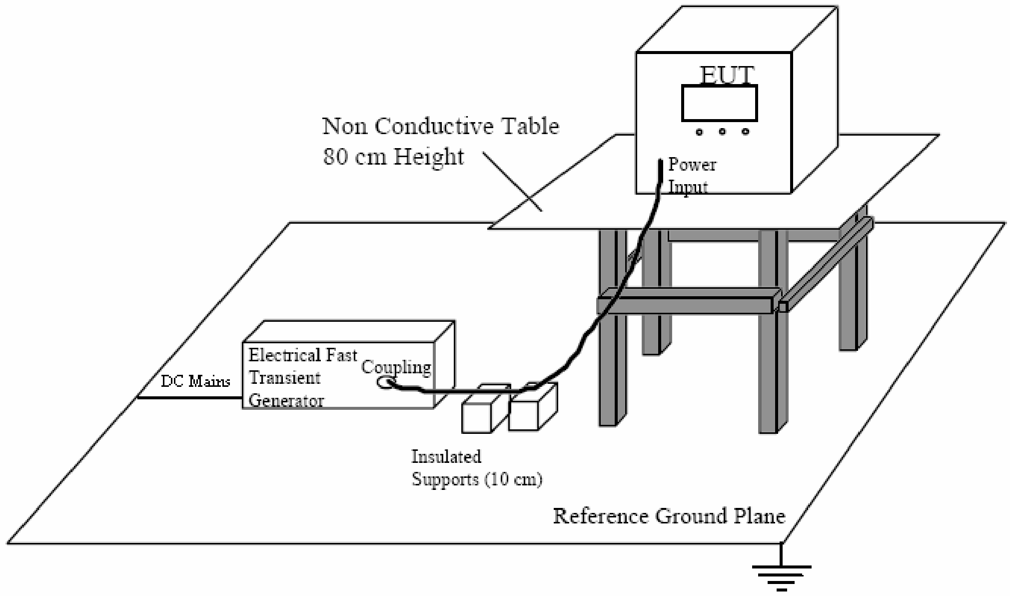


Figure 5-35: IEC 61000-4-4 Typical Test Setup

5.5.4 EFT Generator

Simplified schematic diagram of the EFT generator is given in Figure 5-36. EFT pulse is injected through 50Ω using the discharge switch. Typical current waveform at the output of the generator was shown in Figure 5-25 in part 5.4.1.1.

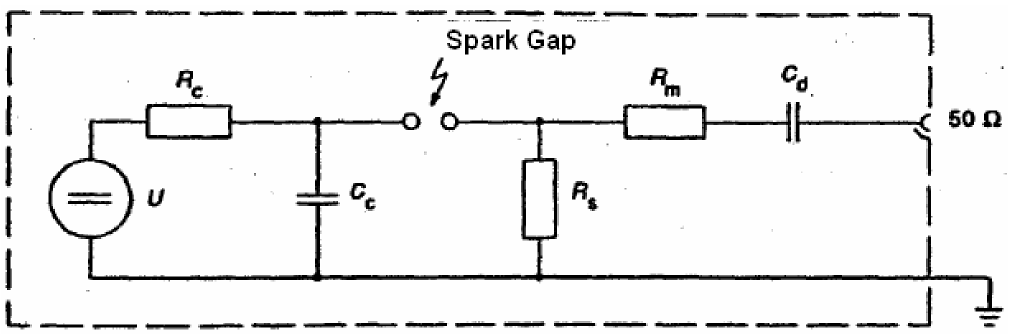


Figure 5-36: Simplified schematic of EFT generator

5.5.5 Measurement and Results

EFT pulse mentioned in part 5.4.1.1 is injected first to the positive line and then to the ground line both for duration of one minute. Applied burst period is 300 milliseconds and frequency of the pulses in every burst is 5 kHz. This means at least 130 bursts are injected to the power supply input of the EPQM. Figure 5-37 shows the EPQM under EFT test.

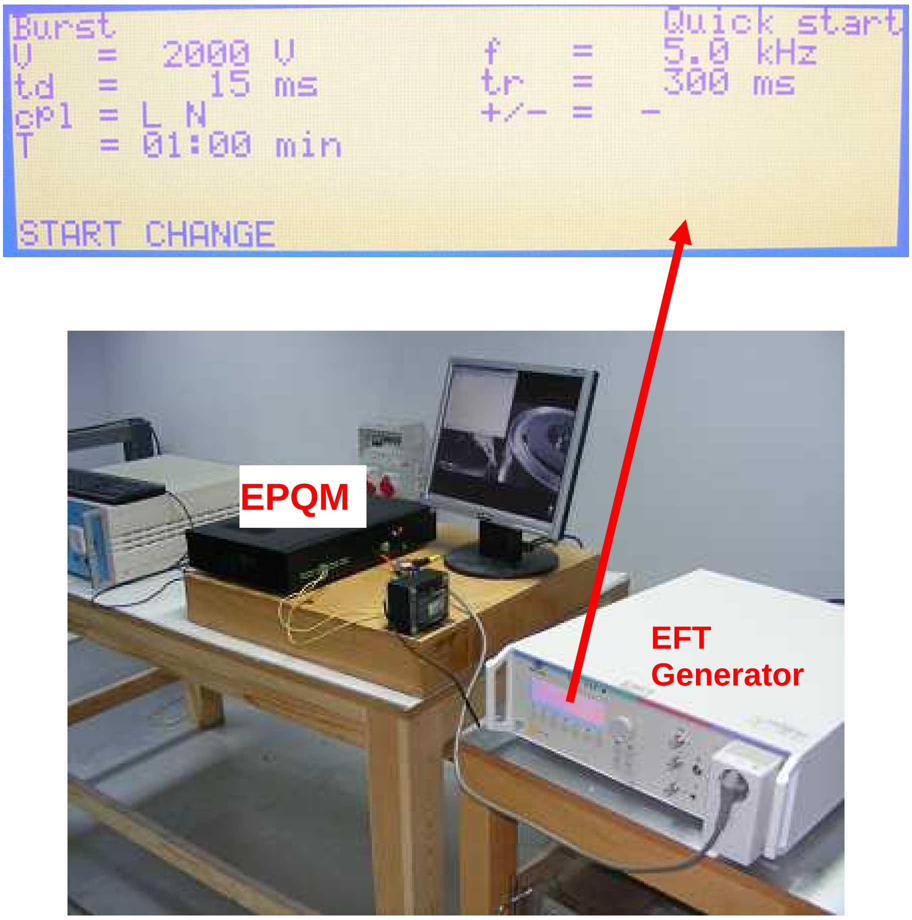


Figure 5-37: EPQM under EFT test

The filter circuit with transient protection in part 5.4.2 is used in front of the power supply input of the EPQM. Chassis connections of the filter circuit with the box and the reference ground plane are shown in Figure 5-38.

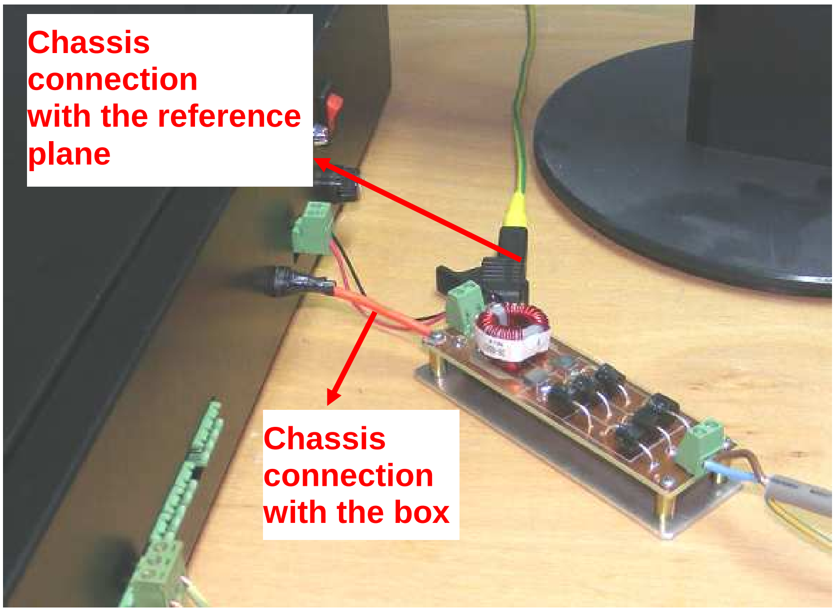


Figure 5-38: Filter in front of the EPQM

During the EFT test, performance of the EPQM is monitored. 15V AC voltage supplied from an isolated 220V/15V AC transformer is applied to the voltage measurement input of the device as was done in ESD test and the measurement program on the EPQM is run. No change in reading is observed and also there is no damage on the device. So, *performance criterion "A"* is satisfied by the EPQM when operating under EFT pulses.

5.6 Surge Immunity Test According to IEC 61000-4-5

5.6.1 Background on Surge Immunity

Surge pulses are the biggest enemies of the equipments/systems operating from the mains supply directly or through other equipments. They can kill the equipments in connection with each other or possibly the whole system. Because these pulses are very slow and have significant amount of energy.

Surges usually give harm to the supply inputs. However they also cause upsets on digital and analog circuits. Digital circuits can make wrong decisions causing loss of function of the device. More critical ICs are the processors. They have the control of the device and any wrong decision of the processor can cause unintended operation of the device, even can give harm to the peripherals.

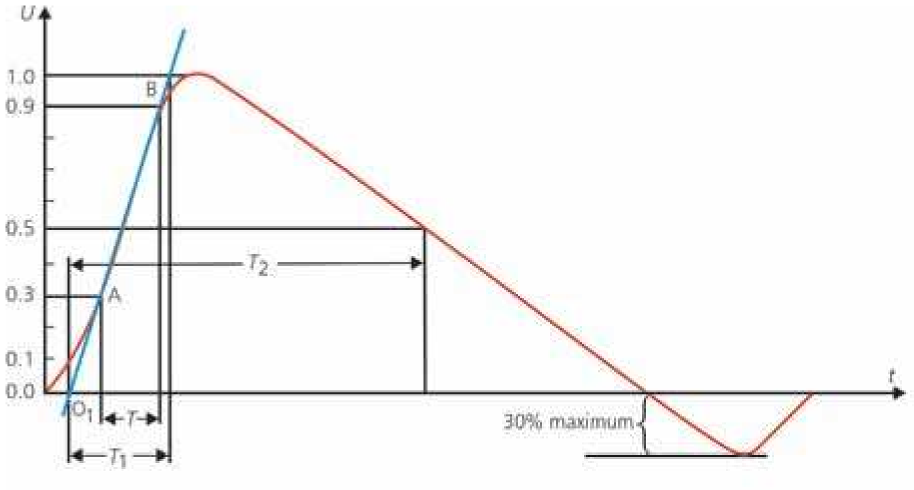
Due to the above facts, performance criteria for surge tests are determined by the manufacturer considering the issues such as high-reliability, mission-critical operation. However usually it is accepted that the device survives from the surge pulse.

5.6.2 Objective of IEC 61000-4-5

The purpose of this test is to evaluate the performance of the EUT when subjected to surges of 1.0 kV on the power lines.

5.6.3 Test Levels

In Table 5.1 test levels for surge pulses are given as 1 kV for dc sourced equipments. These pulses (See Figure 5-39) are injected between positive line and ground of the power supply input.



$T_1 = 1,67 \times T = 1,2\ \mu s \pm \%\ 30$
$T_2 = 50\ \mu s \pm \%\ 20$

Figure 5-39: Surge Pulse with 1 kV Peak Value

5.6.4 Test Setup

IEC 61000-4-5 test setup is basically the same as the test setup in part 5.5.3 given for IEC 61000-4-4. The surge generator is used instead of an EFT generator.

5.6.5 Surge Generator

Simplified schematic diagram of the surge generator is given in Figure 5-40. Typical current waveform at the output of the generator was shown in Figure 5-26 in part 5.4.1.1.

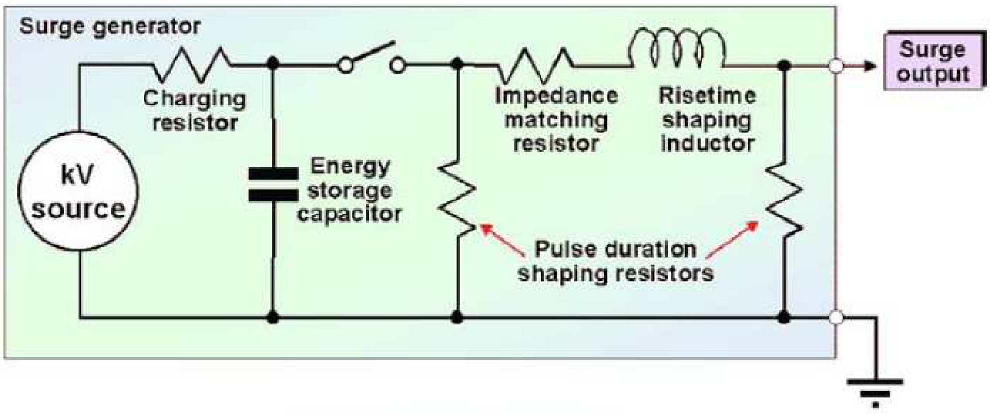


Figure 5-40: Simplified schematic of surge generator

5.6.6 Measurement and Results

Ten surge pulses are injected between positive line to ground of the power supply input for a duration of one minute (See Figure 5-41).

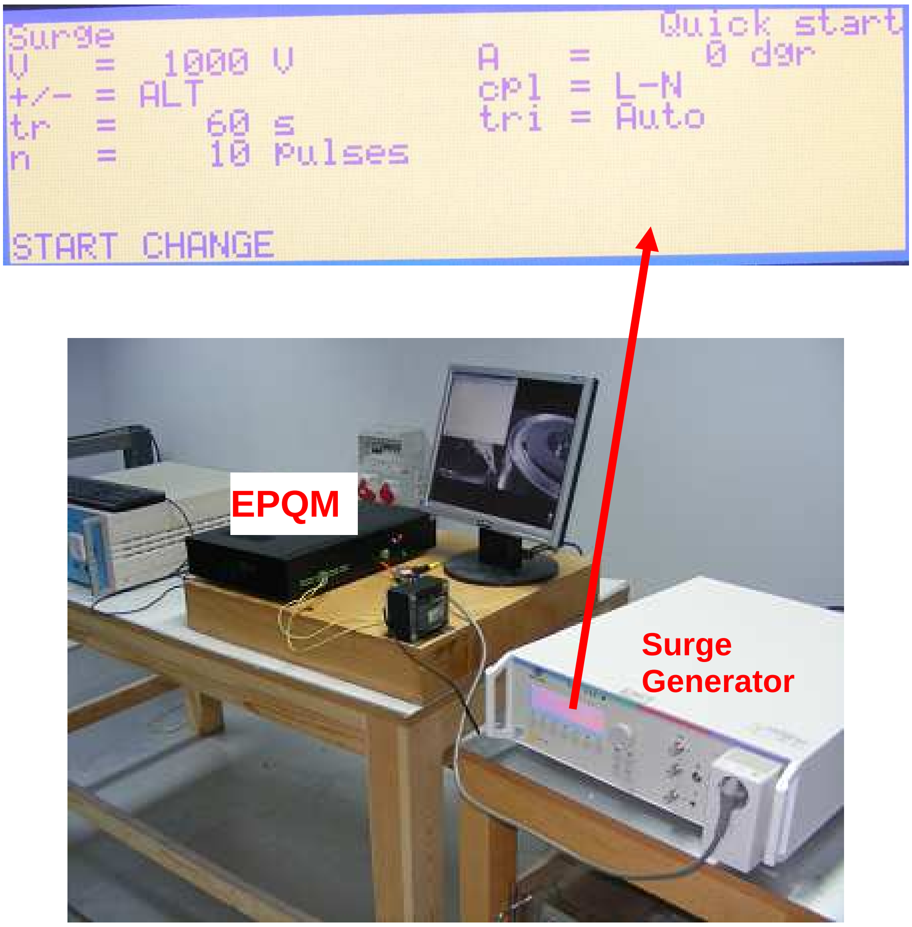


Figure 5-41: EPQM under surge test

The surge pulse has caused the system to reset. As the supply input voltage may be out of the operating range during the surge pulse, the line voltage at the output of the filter is monitored by an oscilloscope. As seen from Figure 5-42, during the surge pulse the maximum level of the voltage seen on the input is 63 V.

Figure 5-42: EPQM supply input under surge test

The transient protection circuit clamps the voltage at 63 V which is below the upper limit of the operating voltage which is 72 V. So there must to be other reasons for the system reset.

One possible reason may be the poor output voltage regulation of the internal DC-DC converter of the EPQM with changing input voltage. However the processor used in EPQM is supplied from ATX power supply unit which is fed from the DC-DC converter. This ATX supply is expected to filter this poor regulation. So the output of the converter must drop so much that the ATX supply can not regulate the output anymore. It is mentioned previously that processors are usually the most sensitive Ics to their input voltages. So this regulation problem may cause the processor to reset the system due to low voltage levels.

Another reason may be the radiated field caused by the surge generator. A similar situation was observed when 30 V/m radiated field was applied to the device in IEC 61000-4-3 test. Around 100 MHz, EPQM has gone in system reset. However it is difficult for the surge generator to produce 30 V/m around 100 MHz to cause the same problem. So voltage regulation seems to be the more likely reason for this system reset.

5.7 Conducted RF Immunity Test According to IEC 61000-4-6

5.7.1 Background on Conducted RF Immunity

Conducted RF immunity simply refers to a product's immunity to unwanted “noisy” RF voltages and currents carried by its external wires and cables [44].

But what causes the wires and cables to carry this “noisy RF currents or voltages? The modern world is fully occupied by the wireless technologies such as cell phones, Wi-Fi, Bluetooth. These technologies work with the transmit/receive RF signal principal. Because of their RF signals, these communication devices are handled as noise sources for other devices and immunity to these RF signals should be studied carefully.

This immunity comes forward in two types. One is the radiated RF immunity, which was tested in part 5.3, and the other is the conducted RF immunity which will be tested now. Radiated electromagnetic fields can disturb the equipment by inducing currents and voltages on its outer cables.

5.7.2 Objective of IEC 61000-4-6

This standard evaluates the immunity of the equipments against the conducted electromagnetic field occurred on their outer cables because of the radiated field in the operating environment.

5.7.3 Test Levels

In Table 5.1 test level for conducted RF immunity is given as 3 V. As the I/O cables are not longer than 3 meters, this conducted RF will only be applied to the power supply input of the device.

5.7.4 Test Setup

Typical test setup for IEC 61000-4-6 applied to the power lines is shown in Figure 5-43.

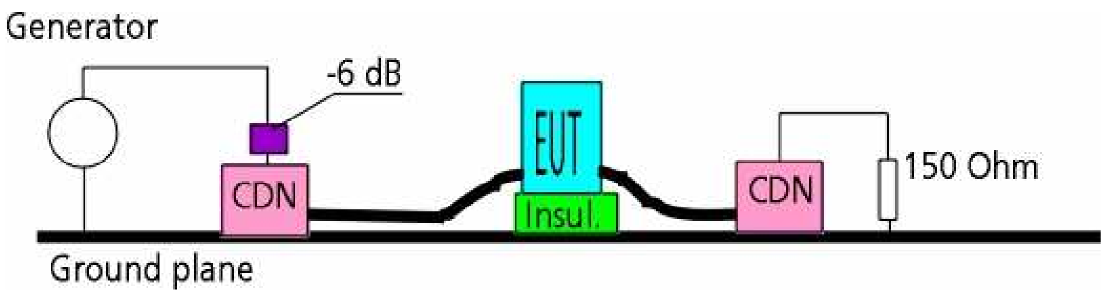


Figure 5-43: IEC 61000-4-6 Typical Test Setup

The test set up consists of a large ground plane that is at least 100 mm larger at 4 sides then the full test set up. In the center the EUT is placed on an insulating layer of 100 mm. All cables are led to and from the equipment at heights of 30 mm and pass through a standard Coupling Decoupling Network (CDN) [45].

On all wires inside the cable a current is induced with an EMF value equal to the required test level (1 – 10 Volts rms into 150 ohm at 80% AM) and at a frequency between 150 KHz up to 80 MHz. This voltage induces a current into the wire leading to the EUT equal to V/150 mA. As all cables are connected to ground via a CDN, this current will find its way through the EUT to all other cables connected and back to the ground plane, effectively simulating the effect of real life EM-field induced RF-current effects [45].

5.7.5 Measurements and Results

Test site configuration for conducted RF immunity is shown in Figure 5-44. 15V AC voltage supplied from an isolated 220V/15V AC transformer is applied to the voltage measurement input of the device and the measurement program on the EPQM is run. During the injection of the conducted RF, no change in reading is observed. So, *performance criterion "A"* is satisfied by the EPQM under conducted RF.

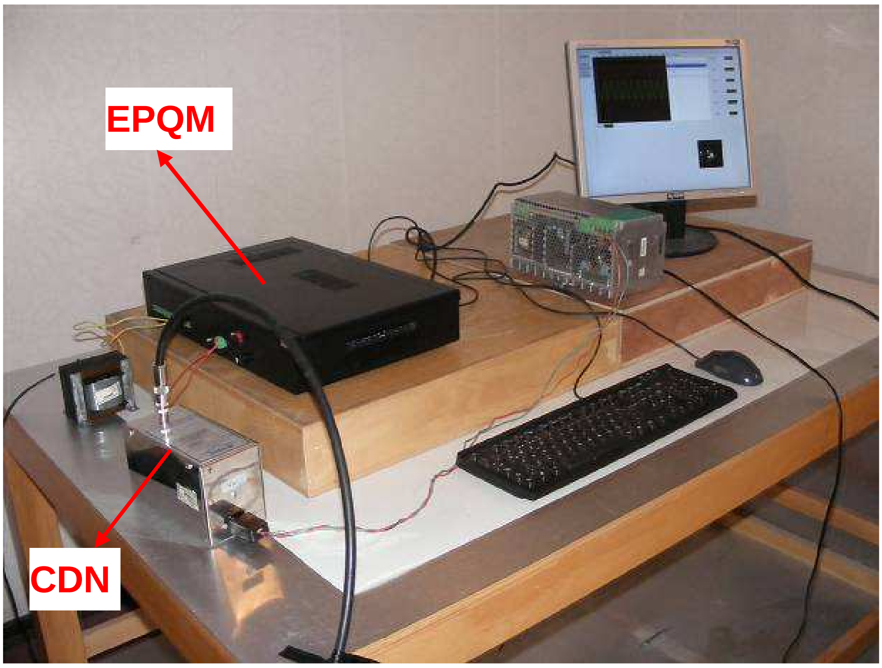


Figure 5-44: EPQM under conducted RF

CHAPTER 6

CONCLUSIONS AND FURTHER WORK

In this thesis, the EMC of EPQM has been investigated in order to ensure that accurate measurement results are taken in the field under disturbances, and without disturbing other equipments.

For electromagnetic compatibility against radiated and conducted emissions, EPQM has been tested according to CISPR11 standard. This standard is given as a reference emission standard in EN 61326 for ISM equipment. As EPQM will be used in industrial environment, it is appropriate to keep the emissions below the limits defined in this standard.

Without any precaution, it has been shown that the conducted emission of EPQM does not stay below the limits. Terminal disturbance levels show that the power supply unit injects noise to the power line around 200 kHz, which corresponds to the switching frequency of the DC-DC converter in the power supply unit. Harmonics of this switching frequency at 400 kHz and 600 kHz have also been found above the limits. At higher frequencies, EPQM has disturbed the supply input and this disturbance was also above the limits. Solving the problem becomes very difficult especially if one deals with each frequency separately. Instead, solving the problem by separating the common mode and differential mode noise has been applied as a more efficient method. Measuring the common mode and differential mode currents on the supply line helps us to predict required attenuation levels for each mode of noise. EMI filter designed according to these required attenuation levels has fixed the terminal disturbance problem of EPQM.

Terminal disturbance measured with the designed filter has been reduced below the limits specified in the given standard by EMI filtering.

CISPR11 standard also gives requirements for radiated noise caused by the device. It is known that radiated emissions are related with the conducted emissions, and high terminal disturbance levels usually show themselves in radiated EMI. So, EMI filtering affects not only the conducted emissions, but the radiated emissions too. According to the radited emission tests performed, radiated noise observed in GTEM cell without EMI filtering was found above the limits, as expected. With the designed filter the radiation was kept below the limits defined in the standard. The results with and without the chassis connection have given us a good idea about the performance criterion of the designed filter. A wide chassis connection is needed for a good performance of the filter. The chassis of the EPQM seems to be suitable for this purpose, as seen from the results. Installing the designed filter inside the EPQM and making a good chassis connection will fix both the radiated and conducted noise problem.

In order to figure out the performance of the device under radiated and conducted disturbances, immunity tests defined in EN 61326 have been applied to the device.

First one was the immunity to ESD events defined in IEC 61000-4-2. High performance under this test is important as ESD is a user originated event and occurs very frequently. ESD usually jumps from one point to another. ESD caused problems arise when this jump becomes to the electrical circuits of the equipment. So ESD exposed to any hole or joint can cause damage to the equipment. It is important to take countermeasures before the ESD test, because the device may no longer function after this test. In fact some countermeasures may be unnecessary, however it has to be ensured that the device will not fail.

The joints on EPQM seem less problematic because of the nonconductive covering on EPQM. If the pieces of EPQM were covered with a conductive material, ESD would probably jump inside, however it is difficult for ESD to travel between non-conductive materials. The slots on EPQM placed for air flow are the possible weak points for ESD event. So covering them with a copper material seems to be a good precaution before conducting ESD test to the device. Test results show that EPQM under ESD satisfies the performance criteria “A”. However, it is obvious that a method for cooling should be found other than leaving slots on EPQM if immunity to ESD is desired. Another method can be limiting the longest dimension of any opening to $^{1}/_{20}th$ of a wavelength at the highest frequency of concern as mentioned in part 2.6.7.3.

Another immunity that has to be checked is the immunity against electromagnetic field radiation, because, it is known that the operating environment of EPQM will be very noisy. EPQM may have to operate for hours or days continuously in noisy environments. Performance of the device under electromagnetic field radiation can be evaluated by IEC 61000-4-3. The immunity level chosen by concerning the operating environment of EPQM is 10 V/m. This is the level defined also for the equipment used in industrial environments. If EPQM is accepted as a counter device, the results show that EPQM can operate continuously under this field with performance criteria “B”. However, it is a fact that there is a possibility for higher interference sources to be placed near EPQM. So being immune to higher electromagnetic fields may be a good criterion for high performance of EPQM. 30 V/m is adequate for simulating the possible higher interefence sources. Under this field, it is observed that EPQM goes in reset around 100 MHz. Covering the slots and connector openings with aluminum foil is not enough to prevent this system reset. A solution may be concentrating the research on the power supply unit. A simple precaution for this problem could be the shielding of the power supply unit with a metal cover for EMI protection.

Other disturbances to be dealed with carefully are the transients. Because a device connected to the power mains can be easily disturbed by transients. Any mechanical switch, relay or motor connected to power mains can cause fast transients on the power line. Lightning event is another example of transient source. For this case, transient pulse is slow and with higher energy. For the possible power disturbances on the power input of EPQM, EFT signals defined in IEC 61000-4-4 and surge pulse defined in IEC 61000-4-5 have been applied to the power supply input. Before the tests, a transient suppressor circuit was designed in order to protect EPQM. This transient circuit was placed in front of the EMI filter previously designed. Using this new filter on the power supply input, performance criteria “A” was satisfied by EPQM under EFT pulses. At the same time, the surge pulse has caused EPQM to go in system reset. The device could be operated again after inhibiting the processor inside. This means that, surge pulse does not cause damage to the device and the function can be restored by the user. So performance criteria “C” can be satisfied by EPQM. Surge pulse test is a serious test for devices, and sometimes performance criteria “C” can be acceptable. Usually, the aim is to stay alive after a lightning event, however for a higher performance criterion, power supply unit has to be studied carefully. The voltage level seen on the input of the device at the instant of surge pulse injection was below the maximum operating voltage level of the power supply unit. The regulation problem mentioned before can be fixed by using large capacitors at the output of the DC-DC converter to prevent rapid changes of voltage.

In IEC 61000-4-6 test, the effect of wireless communication is tried to be simulated. EPQM continues to operate without being disturbed by conducted RF on its power supply cable. So, performance criteria “A” is satisfied by EPQM.

Results and conclusions mentioned up to now are summarized in Table 6.1.

Table 6.1: Results and Conclusions

		NAME OF THE TEST	RESULTS	CONCLUSIONS
EMISSIONS	CONDUCTED	CISPR11	PASSED	• *EMI filter* has been designed.
	RADIATED	CISPR11	PASSED	• EMI filter has been used. • *Chassis connection* with the EPQM box is needed.
IMMUNITY	ESD	IEC 61000-4-2	PERFORMANCE CRITERION "A"	• The joints seem less problematic because of the nonconductive covering. • *The slots* are the possible weak points for ESD event. • *A method for cooling* should be used other than leaving slots such as limiting the longest dimension of any opening to *1/20th of a wavelength* at the highest frequency of concern
	RADIATED RF	IEC 61000-4-3	PERFORMANCE CRITERION "B"	• Result is given for an electric counter device. • For a power quality monitor, performance criterion level should be determined by considering the effect of found error rate on the normal operating. • For 30V/m RF field immunity, the research should be concentrated on the power supply unit. • A simple precaution could be the *shielding of the power supply* unit with EMI protective cover.

Table 6.1 (cont'd)

		NAME OF THE TEST	RESULTS	CONCLUSIONS
IMMUNITY	EFT/BURST	IEC 61000-4-4	PERFORMANCE CRITERION "A"	• *Transient protection circuit* has been used in front of the power supply input.
	SURGE	IEC 61000-4-5	PERFORMANCE CRITERION "C"	• Usually, the aim is to *stay alive* after a lightning event. • *Transient protection circuit* has been used in front of the power supply input. • EPQM has gone in *system reset* • Surge pulse does not cause damage to the device and the function can be restored by the user. • For a *higher performance* criterion, power supply unit has to be studied carefully.
	CONDUCTED RF	IEC 61000-4-6	PERFORMANCE CRITERION "A"	• EPQM continues to operate without being disturbed by conducted RF on its power supply cable.

In summary; emissions of the device kept below the limits and immunity of the device has been evaluated by giving the performance criterion levels for each defined test in the standard. The study has been focused on the first prototype of national power quality monitors developed by Tübitak-Uzay. Same test procedures as those given in this thesis can be applied and electromagnetic compatibility of the newer versions of the prototype can be satisfied by taking similar countermeasures.

Test sites and equipment used for the applied tests are given in Table 6.2.

Table 6.2: Test sites and equipment for applied tests

		NAME OF THE TEST	TEST SITE	COMPANY	MODEL NUMBER AND NAME	CALIBRATION VALID UNTIL
EMISSIONS	CONDUCTED	CISPR11	ASELSAN EMC LABORATORIES	AGILENT	E7405A EMC ANALYZER	10.05.2008
				SOLAR	9233-50-TS-50-N LISN	15.12.2007
				AGILENT	6032A POWER SUPPLY	10.05.2008
				SUHNER	6500-17-A 50Ω TERMINATION	Need no calibration
				SCHAFFNER	“EMC COMPLIANCE 3” SOFTWARE	Not Applicable
		CM&DM MEASUREMENTS	ASELSAN EMC LABORATORIES	AGILENT	E7405A EMC ANALYZER	10.05.2008
				SOLAR	9233-50-TS-50-N LISN	15.12.2007
				SOLAR	6741-1 RF CURRENT PROBE	15.12.2007
				AGILENT	6032A POWER SUPPLY	10.05.2008
				SUHNER	6500-17-A 50Ω TERMINATION	Need no calibration
				SCHAFFNER	“EMC COMPLIANCE 3” SOFTWARE	Not Applicable
	RADIATED	CISPR11	ASELSAN EMC LABORATORIES	AGILENT	E7405A EMC ANALYZER	10.05.2008
				SCHAFFNER	GTEM1750 Test Cell	17.11.2008
				AGILENT	6032A POWER SUPPLY	10.05.2008
				SCHAFFNER	“EMC COMPLIANCE 3” SOFTWARE	Not Applicable

Table 6.2 (cont'd)

		NAME OF THE TEST	TEST SITE	COMPANY	MODEL NUMBER AND NAME	CALIBRATION VALID UNTIL
IMMUNITY	ESD	IEC 61000-4-2	ELDAŞ EMC LABORATORIES	EM Test	DITO ESD Simulator	01.09.2009
	RADIATED RF	IEC 61000-4-3	ELDAŞ EMC LABORATORIES	Schwarzbeck	STLP 9128E E Stacked Douple Log-Per.Antenna (65MHz - 3GHz)	04.07.2010
				Ets-Lindgen	HI-6005 RF Electric Field Probe (500V/m-6GHz)	28.03.2009
				Rohde&Schwarz	SML03 Signal Generator (9kHz-3.3GHz)	07.05.2010
				ELDAŞ	EMC Project	Not Applicable
	EFT/BURST	IEC 61000-4-4	ELDAŞ EMC LABORATORIES	EM Test	UCS 500 M4 Ultra Compact Simulator	01.09.2009
	SURGE	IEC 61000-4-5	ELDAŞ EMC LABORATORIES	EM Test	UCS 500 M4 Ultra Compact Simulator	01.09.2009
	CONDUCTED RF	IEC 61000-4-6	ELDAŞ EMC LABORATORIES	EMC Electronic	CDN-M3 Coupling Decoupling Network (150kHz-230MHz, 16AMP)	22.07.2008
				Rohde&Schwarz	SML03 Signal Generator (9kHz-3.3GHz)	07.05.2010
				ELDAŞ	EMC Project	Not Applicable

REFERENCES

[1] SCHAFFNER, Power Quality – Increased Reliability Brochure

http://www.schaffner.com/components/en/level1/_pdf/level16.pdf, November 23, 2007

[2] C. SANKARAN, Power Quality, by CRC Press LLC, 2002

[3] Philippe FERRACCI, Schneider Electric, Cahier technique no. 199, Power Quality

[4] Devender, K.Nageswara Rao, K.Suryanarayana, Shanta Sarvade, D.Ramesh, "Electromagnetic Interference (EMI) Suppression Techniques – A Case Study", *Electromagnetic Interference and Compatibility, 2002. Proceedings of the International Conference* on 21-23 Feb. 2002

[5] Marco Chiadio Caponet, Francesco Profiuno, Alberto Tenconi, "EMI Filters Design for Power Electronics", *Power Electronics Specialists Conference*, 2002. pesc 02. 2002 IEEE 33rd Annual Volume 4, 23-27 June 2002

[6] Sheng Ye, Eberle W., Yan-Fei Liu, "A novel EMI filter design method for switching power supplies", *Power Electronics, IEEE Transactions* on Volume 19, Issue 6, Nov. 2004 Page(s):1668 - 1678

[7] Cadirci, I., Saka, B., Eristiren, Y., "Practical EMI-filter-design procedure for high-power high-frequency SMPS according to MIL-STD 461", *Electric Power Applications*, IEE Proceedings-Volume 152, Issue 4, 8 July 2005

[8] Oren Hartal, Electromagnetic Compatibility By Design, 3rd Edition, 1995

[9] FLUKE Electronics, Fluke 1750 Three-Phase Power Quality Recorder

[10] FLUKE Electronics, Fluke 345 Power Quality Clamp Meter

[11] NASA Reference Publication 1368 – Marshall Space Flight Center Electromagnetic Compatibility Design and Interference Control (MEDIC) Handbook CDDF Final Report, Project No. 93-15

[12] BurrBrown, Application Note, Noise and Interference

www.nalanda.nitc.ac.in/industry/AppNotes/BurrBrown/appnotes/DesignSem3.pdf, November 17, 2007

[13] Compliance Engineering_Archive documents-EMCStandards61

http://www.ce-mag.com/99ARG/EMCStandards61.html, November 17, 2007

[14] Wikipedia-The Free Encyclopedia, Electromagnetic Compatibility

http://en.wikipedia.org/wiki/Electromagnetic_compatibility, November 17, 2007

[15] Tim Williams, Emc For Product Designers, Newnes, Third Edition, 2001

[16] Mark I. Montrose, EMC and Printed Circuit Board Book, IEEE Electromagnetic Compatibility Society, 1999

[17] Robert Richards, EMC Related Formulas, March 30, 2003

[18] ASTEC Application Notes, Doc No:1821, REV. 03, December 11,1998

[19] Fairchild Semiconductor, Application Note 4145, Electromagnetic Compatibility for Power Converters, REV. 1.0, June 4, 2004

[20] Thuyen Dinh, Pulse Company, EMC Issues Concerning Magnetic Interfaces

http://www.pulseeng.com/products/datasheets/G212.pdf, November 17, 2007

[21] Mark I. Montrose and Edward M. Nakauchi, Testing for EMC Compliance, Approaches and Techniques, IEEE Electromagnetic Compatibility Society, 2004

[22] Fundementals of ESD, Electrostatic Discharge Association, 29th EOS/ESD Symposium, September 16-21, 2007 – Anaheim CA

[23] Daryl Gerke and Bill Kimmel, EDN, The Designer's Guide to Electromagnetic Compatibility, 2004

[24] Dr David D. Ward, Electrostatic Discharge, The Institution of Electrical Engineers, 1999

[25] Jim Lepkowski, ON Semiconductor Application Note, An Introduction to Transient Voltage Suppression Devices, Rev. 0, July, 2005

[26] John R. Barnes, Robust Electronic Design Reference Book, 2004

[27] Bruce Hartwig, VISHAY Semiconductors Application Note, March 1, 2004

[28] EPCOS – EMI suppression capacitors

http ://www.epcos.com/web/generator/Web/Sections/ProductCatalog/EMCComponents/EMCComponents/EMISuppressionCapacitors/PDF/PDF__General__Standards,property=Data__en.pdf ;/PDF_General_Standards.pdf, November 17, 2007

[29] CONIS Company, Suppression Capacitors

http://www.conis-bg.com/downloads_pdf/EMI%20and%20RFI%20filters/suppression%20capacitors.pdf, November 17, 2007

[30] Murata Company, Application Note TE04EA-1

http://www.murata.com/emc/knowhow/pdfs/te04ea-1/26to28e.pdf, November 17, 2007

[31] CWS Company, Application Note, Understanding EMC Standards and Specifications

http://www.coilws.com/AppNotes/EMC.html, November 17, 2007

[32] EN 61326/A1 : 1998, EN 61326/A2 : 2001 Std. – *"Electrical equipment for measurement, control and laboratory use – EMC requirements"*

[33] Douglas C. Smith, Al Wallash, *"Electromagnetic Interference (EMI) Inside a Hard Disk Drive Due to External ESD"*, 2002 EOS/ESD Symposium Proceedings.

[34] A. Wallash and D. C. Smith, *"Damage to Magnetic Recording Heads Due to Electromagnetic Interference"*, 1998 IEEE EMC Symposium Proceedings, pp. 834-836.

[35] A. Wallash and D. C. Smith, *"Electromagnetic Interference (EMI) Damage to Giant Magnetoresistive (GMR) Recording Heads"*, 1998 EOS/ESD Symposium Proceedings, pp. 368-374.

[36] C. F. Lam, C. Chang, and R. Karimi, *"A Study of ESD Sensitivity in AMR and GMR Recording Heads"*, 1998 EOS/ESD Symposium Proceedings, pp. 360-363.

[37] EN 55011: 1998/A1: 1999 + A2: 2002 Std. – *"Industrial, scientific and medical (ISM) radio-frequency equipment - Radio disturbance characteristics - Limits and methods of measurements"*

[38] Wikipedia-The Free Encyclopedia, "Line Impedance Stabilisation Network"

http://en.wikipedia.org/wiki/LISN, November 17, 2007

[39] Sulekh Chand and Nurul Hasan, Electronics Regional Test Laboratory (North) New Delhi, India, "A practical approach to conducted noise compliance", November, 2002

[40] Schaffner EMC Systems, GTEM Test Cells, March, 2002

[41] ETS-LINDGREN Company, Model 5400 Series GTEM Operational Manual, March, 2007

[42] Edward R. Richard, INTEGRITY Desing&Test Services, Inc., "Solid State Energy Meter" Report No. 64567.c1, September 13, 1999

[43] Mel Clark and Kent Walters, Microsemi Company, "Determining Clamping Voltage Levels for a Range of Pulse Currents", July 18, 2001

[44] Keith Armstrong, Cherry Clough Associates, A Practical Guide to EN 61000-4-6, January 25, 2007

[45] CE-TEST Qualified Testing BV, Conducted Immunity test set up

http://www.cetest.nl/bench_top.htm, November 21, 2007

APPENDICES

APPENDIX A

SPECIFICATIONS OF THE FILTER COMPONENTS

The specifications of the chosen components in part 4.4.3.2 for the filter design are given below.

Specifications of chosen C_X:

For C_x capacitance, 1210 package 1 µF valued product of AVX Company X5R dielectric capacitors shown in Figure A-1 is chosen.

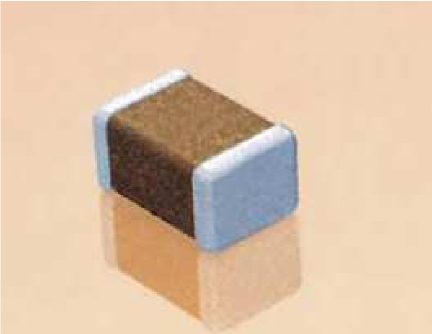


Figure A-1: AVX Company X5R Dielectric Capacitors

General description of this product family is given as:

- General Purpose Dielectric for Ceramic Capacitors
- EIA Class II Dielectric
- Temperature variation of capacitance is within ±15% from -55℃ to +85℃
- Well suited for decoupling and filtering applications
- Available in High Capacitance values (up to 100µF)

Temperature coefficient curve and "insulation resistance vs. temperature" curve are given in Figure A-2 and A-3 respectively.

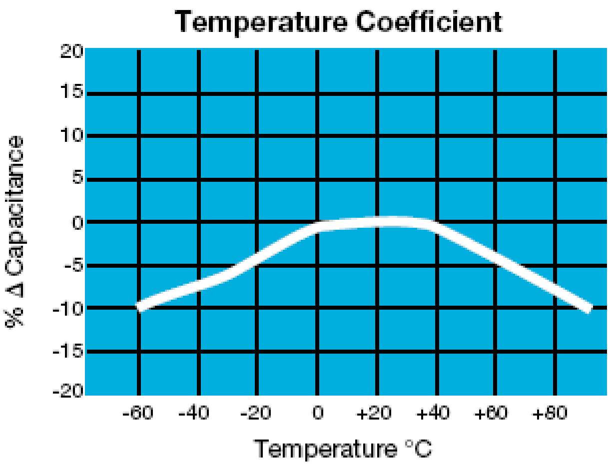


Figure A-2: Temperature Coefficient Curve

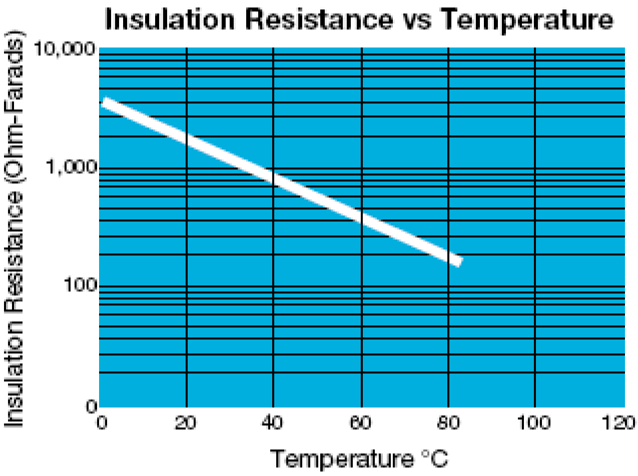


Figure A-3: Insulation Resistance vs Temperature

Specifications of chosen L_d:

For L_d inductance; 4.7 µH valued low profile, high current inductor of VISHAY Company is used (See Figure A-4).

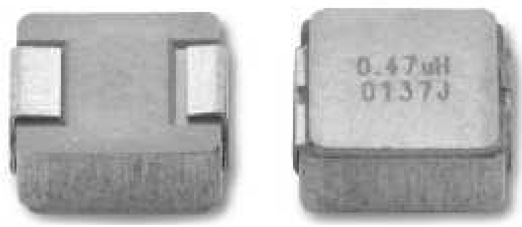


Figure A-4: IHLP-2525CZ-01 product family of VISHAY

General features for this product family is given as:

- Lowest height (3.0 mm) in this package footprint
- Shielded construction
- Frequency range up to 5.0 MHz
- Lowest DCR/µH, in this package size

- Handles high transient current spikes without saturation
- Ultra low buzz noise, due to composite construction 100 % lead (Pb)-free and RoHS compliant

Curves for the inductance and temperature change with continious DC current are given in Figure A-5.

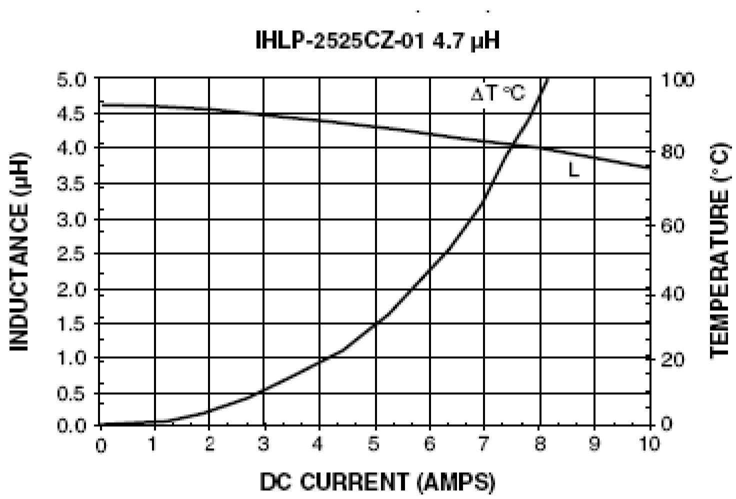


Figure A-5: Performance Graph of IHLP-2525CZ-01 4.7 µH

<u>Specifications of chosen L_C:</u>

For common-mode choke, 36000-37 part numbered product of VICOR Company is chosen. General specifications of the choke is given below:

- L = 330 µH min/coil @1kHz, 250mV
- DCR = 5mΩ max/coil
- Power loss = 3,6W max @20A/coil

A scene of the CM choke and its schematic diagram are shown in Figure A-6.

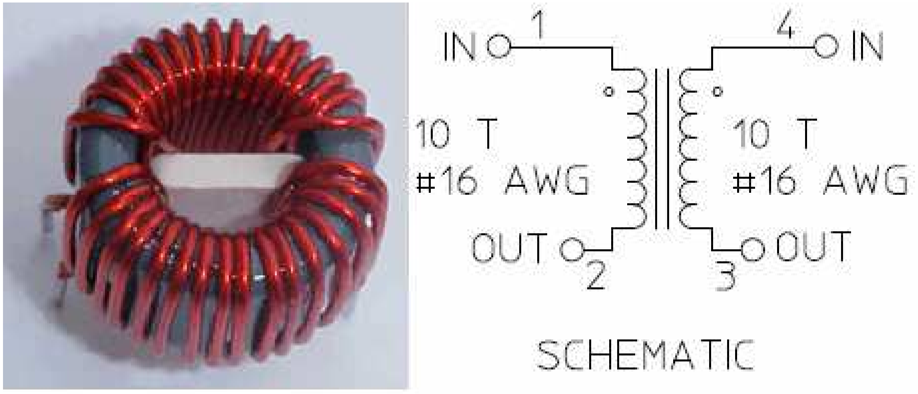


Figure A-6: VICOR 36000-37 part numbered CM choke

Specifications of chosen C_y:

For C_y capacitance, 15 nF valued "GRM31CR72J153KW03L" part numbered product of Murata Company GRM32 series capacitors shown in Figure A-7 is chosen.

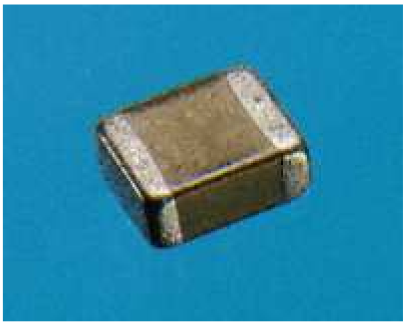


Figure A-7: Murata Company GRM32D series capacitors

Impedance frequency characteristics of GRM32D series capacitors are shown in Figure A-8.

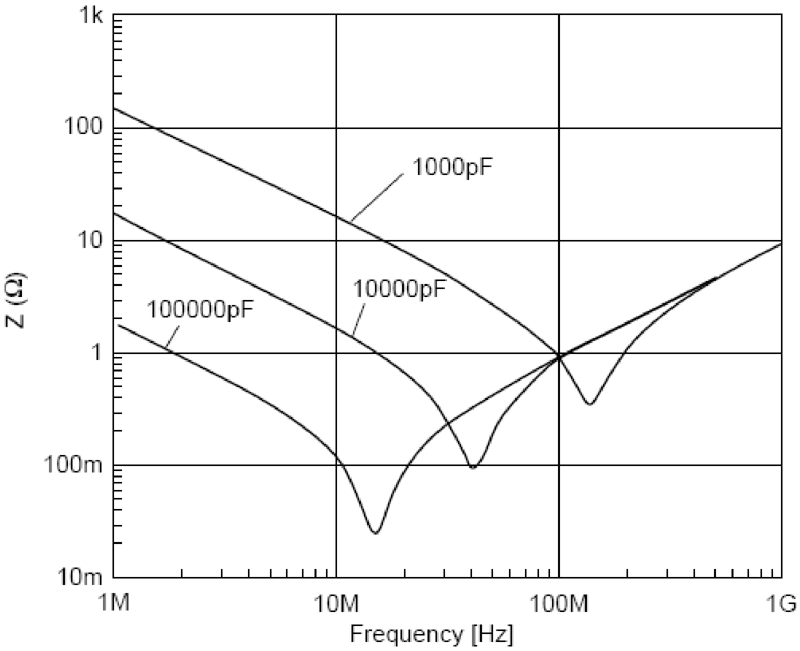


Figure A-8: Impedance vs Frequency Curve for GRM32D